TESTING OF CFRP AT HIGH STRAIN RATES WITH THE SPLIT HOPKINSON TENSION BAR - EVALUATION OF TESTING QUALITY

H. Paul[1], N. Ledford[1], R. Mohrmann[1], M. May[1]

[1]Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Composite Design, Eckerstr. 4, 79104 Freiburg, Germany
Email: hanna.paul@emi.fraunhofer.de, www.emi.fraunhofer.de

Keywords: Testing method, Split Hopkinson Tension Bar, strain rate, Carbon fiber reinforced composite

Abstract
Split Hopkinson Tension Bars are used to test materials at high strain rates under tensile loading. For carbon fiber reinforced composites commonly the specimen are mounted using glued end caps. An alternative mounting concept is presented. The quality of the test results is evaluated using Finite Element Simulations and comparing real test results with two different mountings. The results showed that for low striker velocities of 4 m/s the alternative mounting is suitable. With this alternative approach other specimen dimensions are possible and the testing is less time consuming.

1. Introduction

Within the last years virtual design of components based on finite element models has grown in importance. In order to produce meaningful results in numerical simulations appropriate models for the material behavior including accurate input data are needed. A group of materials which is increasingly used in automotive applications are fiber reinforced composites. There are well established testing procedures to characterize the anisotropic properties of composites in the quasi-static loading regime. One of the critical load cases, which has to be accounted for, in the car design is the crash scenario. During crash, materials are loaded up to strain rates of about 250 s^{-1}. It has been shown that the mechanical behavior of fiber reinforced composites is dependent on the strain rate during loading [1], [2], [3], [4]. Composites are high strength materials with a brittle failure behavior. The properties are beyond that dominated by the laminate and the microstructure. Those characteristics makes testing of composites at high strain rates more challenging than for example testing of metals. Very High Speed (VHS) hydraulic testing machines are commonly used to characterize the material behavior at strain rates which are relevant for the crash scenario [5].

Due to the special characteristics of composites stated above only tests below strain rate of 100 s^{-1} lead to acceptable result qualities with VHS testing machines [6]. To tackle the strain rates between 100 s^{-1} and 250 s^{-1} the Split Hopkinson Bar (SHB) testing is well suited. In these experiments, a specimen is placed between two long elastic rods, the input and the output bar. The input bar is impacted with a projectile inducing a stress wave, which travels through the input bar into the specimen and continues into the output bar. Compared to servo-hydraulic testing machines less mass is accelerated in the system, this results in a better signal quality in SHB experiments. With traditional Split Hopkinson Pressure Bar (SHPB) tests, a specimen is simply placed between the two bars and loaded. However, in a Split Hopkinson Tension Bar (SHTB) test the specimen must be firmly attached to the ends of each bar. The method of mounting and the selected specimen geometry can influence the signal quality significantly. In the following an alternative approach using a mechanical mounting method for the

Excerpt from ISBN 978-3-00-053387-7

testing of fiber reinforced composites in the Split Hopkinson Tension Bar, focusing on tests on carbon reinforced plastic (CFRP) with testing velocities below 5m/s, is presented

2. Testing Method and Materials

2.1. The Split Hopkinson Tension Bar (SHTB)

In this study a recently developed SHTB design based on the concept presented in [9] that allows a longer pulse, an enhanced striker support, and a lower pressure firing chamber was used. The striker is accelerated by a pressurized air system and impacts the transfer flange on the far left. This induces a tensile wave into the input bar which travels through the bar towards the specimen. The bars used for this test series have a diameter of 20 mm and a length of about 9 m for the input and of about 3 m for the output bar (see Figure 1). The material of the bars is titanium. The input and the output bar are mounted with strain gauges at one position each, at the input bar with a distance of 2815 mm to the specimen and at the output bar with a distance of 306 mm. At each strain gauge position four strain gauges are mounted with an angle of 90° to account for bending in the bars. The tension wave is transferred to the specimen after passing through the threaded interface, between the input bar and the mounting hardware.

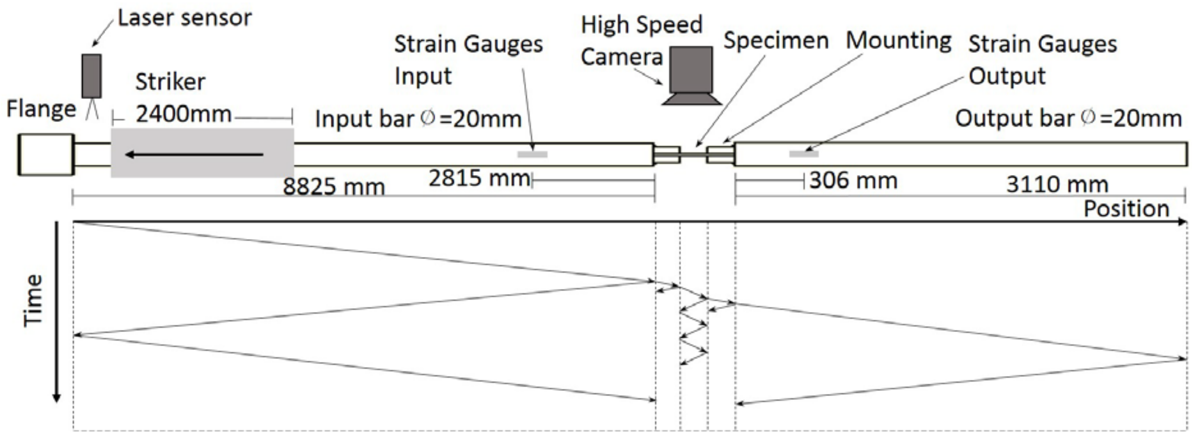


Figure 1. Schematic of Split Hopkinson Tension Bar (SHTB)

The stress within the specimen is determined with the classical non local Split Hopkinson Bar calculation scheme which is based on one-dimensional wave theory using the strain gauges on the output bar [10] .The stress is given by

$$\sigma = \frac{E_{Bo}A_{Bo}}{A_s}\epsilon_{Bo} = \frac{F_{Bo}}{A_s} \quad (1)$$

with the elastic modulus of the output bar E_{Bo} and the cross-section areas of the output bar A_{Bo} and the specimen A_S and the measured strain in the output bar ε_{Bo}. In order to have a direct measurement of the Force F_{Bo} in the output bar, a static calibration of force to voltage at the strain gauges was performed. The classical theory of evaluation of strain based on strain measurements on the input and output bar is based on the assumption that the reduction in cross section area from bar to tested specimen cross section area is sudden and that there is only deformation in the tested section. This assumption is not valid for tension experiments. The mounting and the adhesive bond will also exhibit deformation. Therefore, it is common to measure the strain locally on the specimen. A suitable way to measure strain locally is to use High Speed Cameras and Digital Image Correlation (DIC)

2.2. Material and Specimen Dimensions

In order to evaluate the alternative mounting design a carbon fiber reinforced composite material laminate was used. The thickness of the material was 2.3 mm with an evenly distribution of fiber

Excerpt from ISBN 978-3-00-053387-7

angles of 45°, 90° and -45°. In this investigation a method was to be developed in order to test layups with no fibers in loading direction. Consequently the material was only tested in one direction.
For composites it is critical to ensure that the specimen is large enough that it has a representative volume for the material being tested. This often dictates the minimum length and width of the specimen. In terms of the conducted test the width influences the maximum force which needs to be applied to fail the specimen and the minimum force that the mounting needs to be able to transfer to the specimen. The length of the specimen directly influences the possible strain rate with longer specimen resulting in lower strain rates. The standard specimen dimensions for quasi-static testing are a length 250 mm and width of 25 mm. This is not possible for tests the SHTB. The typical size of composite specimens in the SHTB is a free length of 10 mm and a width of 10 mm. With the alternative mounting concept presented in this paper it is possible to test specimen up to a width of 15 mm. In order to investigate the influence of specimen dimensions on the measured values static tests with three different specimen dimensions which can be used in the SHTB were tested and compared to results from standard tests (width 25 mm and free length 150 mm (25150_qs)). The tested dimensions are width 10 mm and free length 10 mm (1010_qs), width 10 mm and free length 15 mm (1015_qs) and width 15 mm and free length 15 mm (1515_qs). All static tests were performed with a servo hydraulic machine using hydraulic grips. In Table 1 a summary of the strength measured in the quasi-static tests is given. There is significant influence of the dimensions on strength and scatter. The strength drops and scatter rises with smaller dimensions. It is assumed that the drop of strength is dominated by edge effects in the 45° layer. Therefore the strength drops with smaller specimen and does not rise at it is common. It is therefore desired to use specimens as large as possible with this layup during SHTB testing. The minimum size can be different for other layups or loading directions.

Table 1. Influence of specimen dimensions on strength in quasi-static tests

Specimen Type	Dimensions (width in mm, free length in mm)	Normalized Strength	COV in %	Number of Tests
1010_qs	(10,10)	0.84	9.2	3
1015_qs	(10,15)	0.86	4.0	3
1515_qs	(15,15)	0.93	4.0	3
25150_qs	(25,150)	1	1.6	5

3. Alternative Mounting Design

The established specimen for tension tests in the SHTB is an axially symmetric specimen, which engages an internal thread at the end of the bars. However, for materials without axial symmetry such as composites methods of mounting have to be employed. A common approach is to glue threaded metal endcaps on both ends of the specimen and subsequently screw the specimen and the endcaps into the bars. This approach has given good results with small specimens at testing velocities up to 15 m/s [11] [12] [13] [14] but also contains some disadvantages. The specimen preparation is time-consuming and with that costly. In order to get a sufficient load transmission from the endcaps to the composite specimen, high strength adhesive have to be used. Those adhesives often have to cure at temperatures above 150°C. In many cases heating up a polymer fiber reinforced composite to this is extend is not wanted. Endcaps also limit the width of specimens which can be tested. In various applications, the strain rates of interest are in a range that testing velocities in the area of 5 m/s are sufficient. For lower velocities, other mounting concepts can be possible. In the following an alternative approach using a mechanical mounting method for the testing of fiber reinforced composites in the Split Hopkinson Tension Bar, focusing on tests on CFRP with testing velocities below 5 m/s, is presented.

Other than in the mounting with end-caps where the load is transferred with an adhesive joint from to the specimen the alternative concept uses force fit for load transmission. Screws are used to apply a

Excerpt from ISBN 978-3-00-053387-7

normal force to aluminum parts. The aluminum parts have a grooved surface in order to have a higher coefficient of friction between the mounting and the specimen. The ends of the specimens are mounted with glass fiber reinforced polymer tabs. The design of the mounting allows to test specimens with a width up to 15 mm, in order to account for the fact that there is an influence of the size of specimen on the measured values. Figure 2 shows a picture of the mountings including a composite specimen. Similar concepts are used in the VHS to test composites. The concept here is scaled down and with that reduced in mass. The mass of one mounting is 121 g. The mass of to the metal endcaps normally used in SHTB to test composites is 32,5 g. With that the force fit mounting is significantly heavier than the end caps.

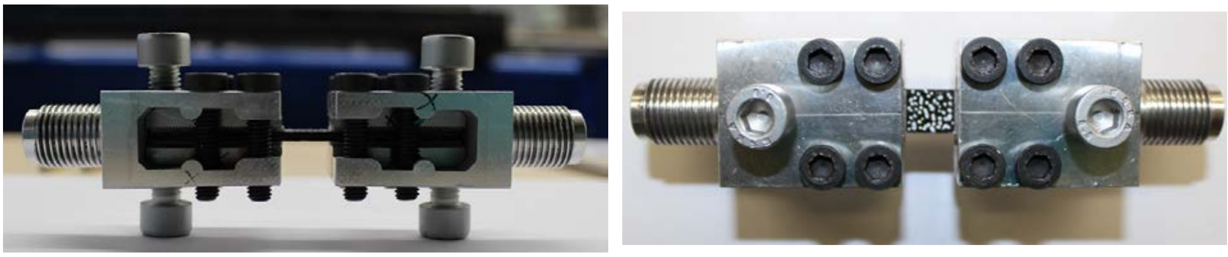


Figure 2. Alternative mounting concept for the SHTB based on force fit.

3.1. Numerical evaluation

In order to evaluate if the alternative mounting concept is suitable for the SHTB finite element simulations were performed. For the finite element simulations an axial symmetric model was used. This is a suitable approach since the main target of the simulations is the investigations on the influence of impedance differences in the bars, the mountings and the specimen and not an exact modeling of the material behavior. The advantage of this approach is that a fine mesh can be used with an acceptable calculation time. But using an axial symmetric models some simplifications had to be made. The striker was modeled as a tube with the same cross-section are as the u-shaped tube. The specimen was modeled as a cylindrical specimen with the same cross-section area as the real flat specimen. The specimen with a free length of 10 mm and a width of 10 mm were used for all simulations. The alternative mounting was as well modeled round and as a solid. The diameter of the mounting was adapted in order to get the correct mass and with that a mean impedance of the mounting. To compare with the behavior of specimens with metal endcaps a second model was simulated. The two models are shown in Figure 3. With both models calculations with two different input pulses, one which is typical for tests at 4 m/s and one at 8 m/s, were performed.

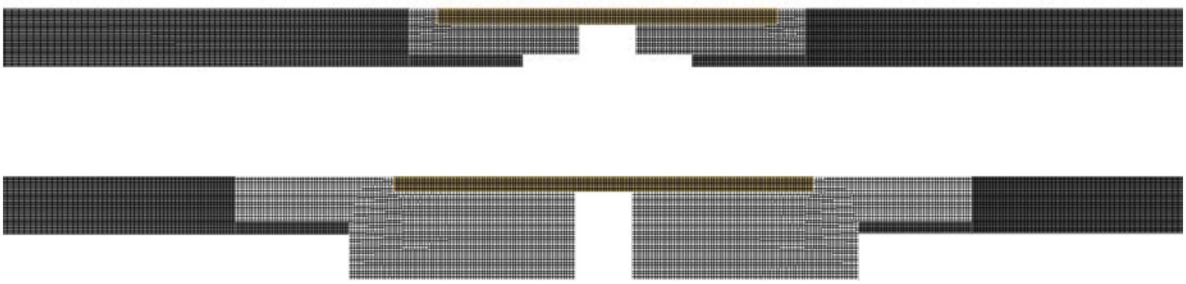


Figure 3. Section with specimen of Finite Element Models of SHTB with a composite specimen with end caps (top) and with the alternative mounting (bottom).

For the material model an elastic-plastic model estimating the material behavior from the SHTB tests with the endcaps (shown in Figure 6) was chosen. Figure 4 shows that with the simple material model

Excerpt from ISBN 978-3-00-053387-7

there is acceptable agreement with an overestimation of strain and an underestimation of strength in the simulation.

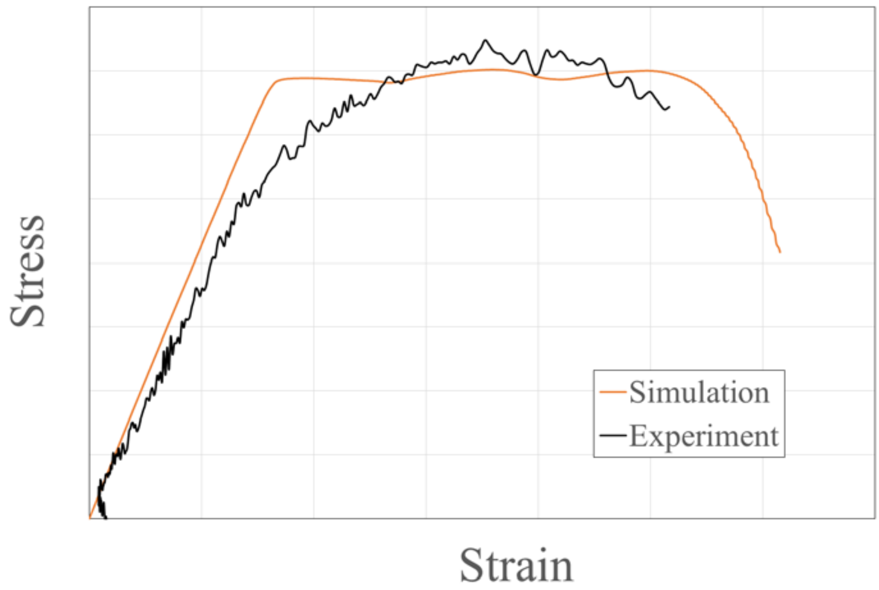
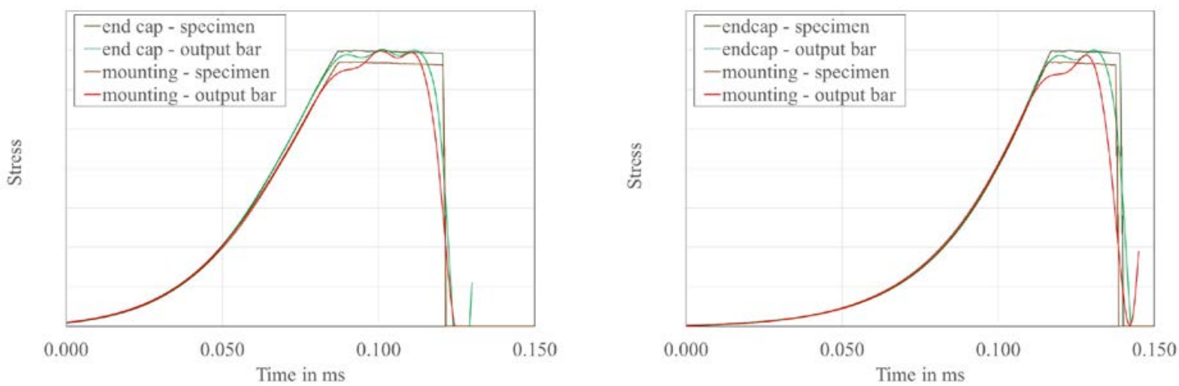


Figure 4. Comparison of stress-strain curve of a simulation with endcaps at a striker speed of 4 m/s

For the calculation of stresses in the specimen it is assumed that the force measured at the strain gauges in the output bar is the same as in the specimen. In order to evaluate if this assumption is valid, forces were analyzed from the simulation results in the middle cross-section of the specimen and compared to the forces at the position of the strain gauges in the output bar. Figure 5 shows the results as stress versus time curves from simulations with a striker speed of 4 m/s (left) and of 8 m/s (right). The forces measured in the specimen are lower for the alternative mounting this is because the failure is induced at the transition between mounting and specimen. The jump in stiffness is higher for the alternative mounting at this position. When comparing the forces measured in the specimen and at the output bar it a difference is observable. The force in the output bar oscillates. The frequency does not change with the different mounting and velocities. But since the test period is lower for higher testing velocities the oscillations are more significant. At the beginning of the plastic deformation there is an underestimation of stress, after wards the simulations with the endcaps converge to the right result from a lower stress. At the simulations with the alternative mounting the stress is overestimated. The amplitude of the simulations is in the range that the force measurement has an accuracy of 5 %. The difference between the measurement at the specimen and in the output bar is higher for the alternative mounting at both velocities, but from the simulations it can be concluded that with striker velocities of 4 m/s the difference is still acceptable, for velocities of 8 m/s the errors might be too big.



Excerpt from ISBN 978-3-00-053387-7

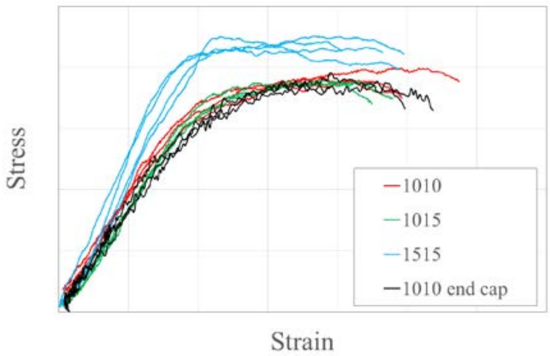
Figure 5. Results from finite element simulations with a striker speed of 4 m/s (left) and of 8 m/s (right)

3.2. Experimental evaluation

In order to investigate the performance of the alternative mounting concept tests with three different specimen dimension were performed. All tests were performed with a striker velocity of 4 m/s. The dimensions were the same as in the quasi-static test: width 10 mm and free length 10 mm (1010), width 10 mm and free length 15 mm (1015) and width 15 mm and free length 15 mm (1515). The test results were compared with experiments performed with the classical mounting concept using end caps. The specimen for those tests had a width of 10 mm and free length 10 mm (1010 endcap). All tests were performed with a striker velocity of 4 m/s. The strength of the tests performed in the SHTB is summarized in Table 2 the stress strain curves are shown in Figure 6. There is no visible influence of the mounting. The tests with the width of 15 mm have a significantly higher strength. The specimens were only the length was changed were at the same level as the short specimen. In comparison with the static tests (see Table 1) the strength values are higher with a much lower scatter. The strain rate calculated from the local strain measurement is as well shown in Figure 6.The striker speed of 4 m/s resulted in a strain rate between 100 s^{-1} and 200 s^{-1} for the specimen with a free length of 15 mm and in a strain rate between 300 s^{-1} and 400 s^{-1} for the specimen with a free length of 10 mm.

Table 2. Influence of specimen dimensions on strength in quasi-static tests

Specimen Type	Dimensions (width in mm, free length in mm)	Normalized strength	COV in %	Number of Tests
1010	(10,10)	1.02	2.2	3
1015	(10,15)	0.99	0.5	3
1515	(15,15)	178	1.7	4
1010 endcap	(10,10)	117	1.8	3



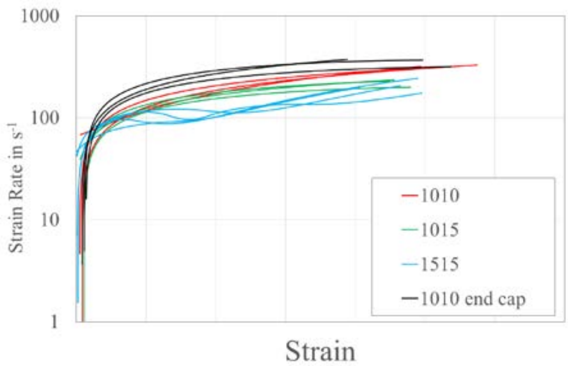


Figure 6. Stress strain curves (left) and strain rate versus strain curves (right) from the tests performed in the SHTB

In Figure 7 the failure patterns of all specimen tested in the SHTB are shown. All specimen failed in the middle and with the same pattern.

Excerpt from ISBN 978-3-00-053387-7

Figure 7. Failure patterns of specimen with end caps (left) and tested in the alternative mounting (right)

4. Conclusions

An alternative mounting concept to test carbon fiber reinforced was developed and its performance evaluated using finite element simulations and an experimental study. The material used for the study had a layup without fibers in loading direction. The finite element simulations showed that for a striker velocity of 4 m/s the error made due to the additional mass of the alternative mounting is acceptable, with velocities of 8 m/s the errors might be too big. The experimental study showed that there is no influence on the results in real tests at 4 m/s. It is concluded that for those specimen the alternative mounting concept is very well suitable.

With the alternative mounting concept it is possible to test specimen up to a width of 15 mm. There are materials, as the one tested in this study, where a significant influence of the width and free length on the measured values can be observed. It is therefore very useful to have the possibility to test wider specimen and high strain rates.

With strain rates of about 200 s^{-1}, this test configuration is very well suitable to characterize carbon fiber reinforced composites without fibers in loading direction in the strain rate regime which is relevant for crash scenarios. With the alternative mounting concept the effort to test in the SHTB is reduced. In future work there will be investigations to improve testing procedures with laminates with fibers in loading directions. For those laminates the transmitted forces from mounting to specimen need to significantly higher.

References

[1] Jacob G, Starbuck J, Fellers J, Simunovic S, Boeman R. Strain Rate Effects on the Mechanical Properties of Polymer Composite Materials. Journal of Applied Polymer Science 2004;94:296-301.

[2] May M, Nossek M, Petrinic N, Hiermaier S, Thoma K. Adaptive multi-scale modeling of high velocity impact on composite panels. Composites Part A 2014;58:56-64.

[3] May M, Measuring the rate-dependent mode I fracture toughness of composites - A review. Composites Part A 2016;81:1-12.

[4] Daniel I, Werner B, Fenner J. Strain rate dependent failure criteria for composites, Composite Science and Technology 2011;71:357-364

[5] May M, Voß H, Hiermaier S. Predictive modeling of damage and failure in adhesively bonded metallic joints using cohesive interface elements, International Journal of Adhesion & Adhesives 2014:4-:7-17

[6] Hamouda A, Hashmi M. Testing of composite materials at high rates of strain: advances and challenges. Journal of Materials Processing Technology 1998;77:327-336.

Excerpt from ISBN 978-3-00-053387-7

[7] Harding J, Welsh LM. A tensile testing technique for fibre-reinforced composites at impact rates of strain. *Journal of Materials Science* 1983;18:1810-1826.

[8] Eskandari H, Nemes J. Dynamic Testing of Composite Laminates with a Tensile Split Hopkinson Bar. *Journal of Composite Materials* 2000;34:260-273.

[9] Gerlach R, Kettenbeil C, Petrinic N. A new split Hopkinson tensile bar design. International Journal of Impact Engineering 2012;50:63-67.

[10] Chen W, Song B. Split Hopkinson (Kolsky) Bar - Design, Testing and Applications, Springer 2011.

[11] Paul H, Ledford H, Ganzenmueller G, Wolfrum J, Petrinic N, May M. Investigations oft he rate and temperature dependent behaiovr of carbon fiber reinforced composites with Split Hopkinson Tension Bar(SHTB) Experiments, submitted to Composite Part A

[12] Gerlach R, Siviour C, Wiegand J, Petrinic N. In- plane and through- thickness properties, failure modes, damage and delamination in 3D woven carbon fibre composites subjected to impact loading. Composite Science and Technology 2015;72:397-411.

[13] Gilat A, Goldberg R, Roberts G. Experimental study of strain-rate- dependent behavior of carbon/epoxy composite. Composite Science and Technology 2002;62:1469-1476.

[14] Gomez-del Rio T, Barbero E, Zaera R, Navarro C. Dynamic tensile behavior at low temperature of CFRP using a split Hopkinson pressure bar. Composite Science and Tecnology 2005;65(1)61-71.

Excerpt from ISBN 978-3-00-053387-7