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# Evaluation of a novel test method for the determination of strain rate-dependent material properties of high-performance fibers

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**Abstract**

For reinforcement in fiber reinforced plastic and concrete applications, the knowledge of the high-velocity impact and crash behavior of typically used high-performance fibers, such as carbon fibers (CF), becomes an important aspect for designing and dimensioning new composite components. More important than the impact velocity is the resulting strain rate in the fiber, which defines the failure behavior. In current literature, there is still an open gap for fiber material testing for strain rates between 100 and 1000 1/s, which is difficult to close with the existing measurement setups, i.e. between servo-hydraulic tensile testing machines and Split-Hopkinson-tension-bars. A rotary drive principle is proposed where the challenge arises in coupling the force, in a reliable clamping of the specimens and in high-speed acquisition of the stress-strain curve. In the implementation process, speeds up to 40 m/s were currently achieved, which corresponds to a strain rate of 267 $s^{-1}$ for a specimen length of 150 mm. The specimen and the moving elements were prepared with stochastic patterns and evaluated by means of digital image correlation (DIC). The force signal is recorded and correlated from a piezoelectric load cell. Additional information on the energy dissipated by the tensile test was acquired by analyzing the engine control records. The evaluation of high-speed images by DIC shows that there is a partially elastic impact and acceleration reaches its maxima before the specimen's rupture. Thus, for a precise evaluation, the stress equilibrium has to be taken into account and the impact process has to be further optimized.


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## 1. Introduction

For any type of engineering construction, a profound knowledge of material characteristics is a crucial factor. In addition to the static behavior, the knowledge of the dynamic material behavior is becoming increasingly important for the design and simulation of innovative construction designs in the fields of automotive and rail (Bleck *et al.*, 2004), aerospace (Gizik *et al.*, 2017), and civil engineering (Schuler *et al.*, 2006; Lindner *et al.*, 2018). The investigations involved in this process differ between metal materials and fiber-reinforced plastics (FRPs). The unique features of fiber-reinforced materials (FRM) consist in their anisotropy and distribution of pressure- and tensile load-absorbing components. Reinforcing fibers mainly absorb the tensile forces; therefore, their tensile test results are an essential aspect in determining the mechanical properties of the overall FRM material. Today, reinforcing fibers used in technical textiles are often made of carbon (CF), glass (GF) or aramid (AR) (Cherif, 2016). ISO 2062:2009 contains regulations for the standardized determination of tensile properties in the quasi-static mode. In contrast, there are still no comparable standards for testing in the dynamic range. However, this area of research is gaining importance in order to make lightweight construction more efficient. Well-founded knowledge of the dynamic behavior of materials should enable a more efficient use of materials and at the same time ensure the structural integrity of a component under dynamic loading.

Although numerous research activities are targeted on novel specific test methods for textiles as well as on reinforcement structures in the field of FRP (Al-Mosawe *et al.*, 2017; Ashir *et al.*, 2018). The current findings on fiber properties at high strain rates are mainly based on research results according to Zhou *et al.*, 2007 and Wang *et al.*, 2008.

Their investigations evaluated material characteristics through a combination of quasi-static and dynamic tensile tests. Due to the operating principle of the employed test devices, there is a lack of measurement values in the strain rate. The aim of the work described in the following is to close this gap in order to cover strain rates from 5 $s^{-1}$ up to 1000 $s^{-1}$ and to provide reliable testing technology.

Dynamic tensile testing covers the very broad range of non-quasi-static tensile tests. The relation with specific dynamic material behavior is established by means of strain rate $\varepsilon$ instead of speed $v_t$. Moreover, the strain rate $\dot{\varepsilon}$ is a time derivation of strain $\varepsilon$ generated during the testing procedure.

The strain rate is therefore the quotient of the applied testing speed and the initial length $l_0$ of the specimen. In the quasi-static range, strain rates of up to 0.01 $s^{-1}$ can be achieved.

**Nomenclature**

| | |
|---|---|
| $\varepsilon$ | strain |
| $\dot{\varepsilon}$ | strain rate |
| $\varepsilon_{Br}$ | strain at break |
| $v_t$ | testing speed |
| $l_0$ | initial specimen length (parallel length of test piece following ISO 26203-1:2018) |
| $c_S$ | wave propagation velocity within the specimen |
| $t_a$ | acceleration time |
| AR | aramid fiber |
| CF | carbon fiber |
| DIC | digital image correlation |
| FRM | fiber-reinforced material |
| FRP | fiber-reinforced plastic |
| GF | glas fiber |

## 2. Experimental

### 2.1. Materials

In order to investigate the performance of the testing system (Fig. 1a), tailored test specimens were prepared. The specimen consists of the technical yarn to be tested, which is bonded into adapted steel elements at both ends. Tenax®-E HTS45 E23 carbon fibers (Toho Tenax, Japan) with a length of approx. 150 mm were used as the technical yarn. The resin system EPIKOTE® RIMR 135 / EPIKURE® RIMH 137 (Hexion, USA) with a mixing ratio of 100:30 was used as adhesive (Unger *et al.*, 2019).

To capture the relevant processes parameters – force and strain rate – during the test, specific sensors were used. For force measurement, the piezoelectric force ring sensor 201B05 was used in conjunction with the amplifier 482C24 (PCB Piezotronics, USA). This was preloaded to measure the effective tensile forces. An optical system based on the high-speed camera SA-X2 1080K (Photron, Japan) was used to measure the strain. A synchronous servomotor from Siemens drives the disc as a precise drive. The servomotor is controlled by a Simotion Control D435 (Siemens, Germany), which allows precise determination of the energy extracted from the rotational system by the impact through its servo cycle of 1 millisecond.

a)

b)

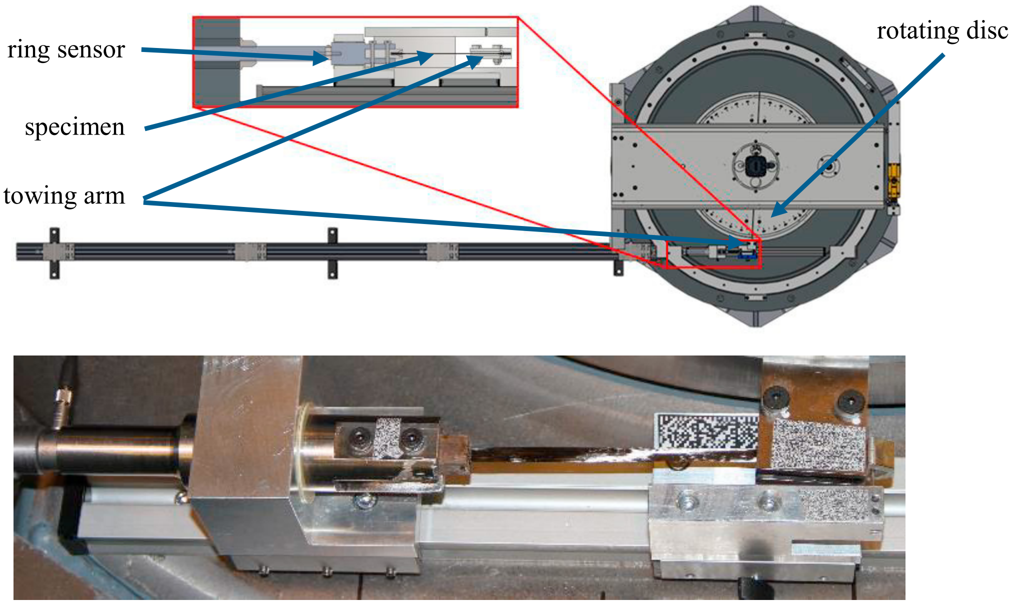


Fig. 1. (a) Test stand with detailed illustration of specimen clamping and force recording; (b) Photo of a clamped specimen with visible DIC markings.

### 2.2. Methods

The design makes it possible to achieve tangential speeds up to 40 m/s in the existing expansion stage. For a given specimen length it is necessary to determine if the state of equilibrium for the stress in the material has been reached in order to assume a valid test. This is to be supposed if the accelerating force pulse and its reflections had enough time to traverse the specimen several times (Parry et al., 1994). Based on specimen length $l_0$, the available time $t_{av}$ until break is calculated by:

$$t_{av} = \frac{l_0 \cdot \varepsilon_{Br}}{v_t} \,,$$

with $\varepsilon_{Br}$ as strain at break and a constant testing speed $v_t$.

This time $t_{av}$ is decreased by the time $t_a$ that is needed to achieve the testing speed during acceleration $a$. If these considerations are merged, the following inequality results:

$$\frac{l_0 \cdot \varepsilon_{Br} - \frac{1}{2} a \cdot t_a^2}{v_t} \geq \frac{n \cdot l_0}{c_s} \text{ with } a = \frac{v_t}{t_a},$$

where $c_s$ is the propagation velocity in the specimen and $n$ the number of traverses. While the time required for the equilibrium is only determined by the propagation velocity, the specimen length and the number of traverses of the signal through the specimen and is, thus, proportional to the specimen length, the available time contains the part of the acceleration required to reach the test velocity. The results presented have been recorded for specimen lengths $l_0$ of 150 mm and thus strain rates up to 267 $s^{-1}$. The inequality is fulfilled for the specimen material and the above given parameters approximately up to $n$=5.

For the experimental setup, the prepared samples were installed in the testing rig and the fixed end, the towing arm and the accelerated sample end were optically marked (Fig. 1b). The camera recording is triggered via an output of the Simotion control system, which automatically initiates the test cycle when the line speed is reached. After a stabilization phase of 20 turns, the mechanical release mechanism is started to the exact angle of an arc in order to prevent a failing test due to a partially hit specimen. The movement and deformation process of the set-up was captured with the high-speed camera at a frame rate of 100,000 fps and a shutter speed of 1/113340 s. Grayscale images with a size of 896 pixels x 128 pixels were captured, which corresponds to an image area of 191.2 mm x 27.3 mm in the sharpness plane with an image scale of 0.2134 mm/pixel. To evaluate the movement of the image parts prepared with stochastic dot patterns, facet sizes of 11x11 pixels, point distance of 7x7 pixels, high accuracy in the evaluation mode and a facet matching against the definition stage in the software GOM Correlate (GOM, Germany) were configured. The force ring sensor mounted behind the sample was scanned at 200 kHz. The measurement data were evaluated with Matlab (MathWorks, USA).

## 3. Results and discussion

To investigate the behavior of the test rig, the courses of the force and the actual speeds of the towing arm and the specimen end (Fig. 2) were recorded simultaneously for the specified test speeds of 40 m/s (Fig. 3).

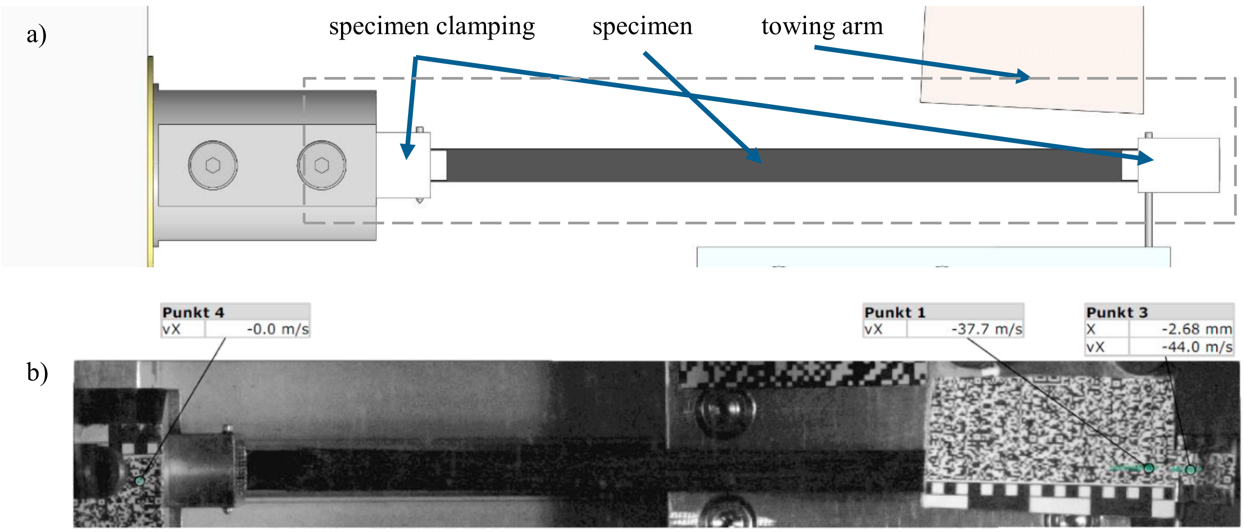


Fig. 2. (a) principle set-up of the specimen holder with marking of the screenshot area; (b) Screenshot of DIC-analysis at the moment of impact

It could be observed that the accelerated end of the specimen reaches the velocity plateau after 20 µs (for 40 m/s) and 30 µs (for 25 m/s), respectively, and thus clearly pre-fracture (Fig. 3).

Figures 3 and 4 show that a negative velocity prevails at the beginning of the movement. If the specimen is not completely parallel to the towing arm in the vertical axis, the towing arm hits the upper and lower sides of the specimen at different times. This triggers an angular momentum until the towing arm reaches the other side. As a result, the one part of the sample moves back briefly.

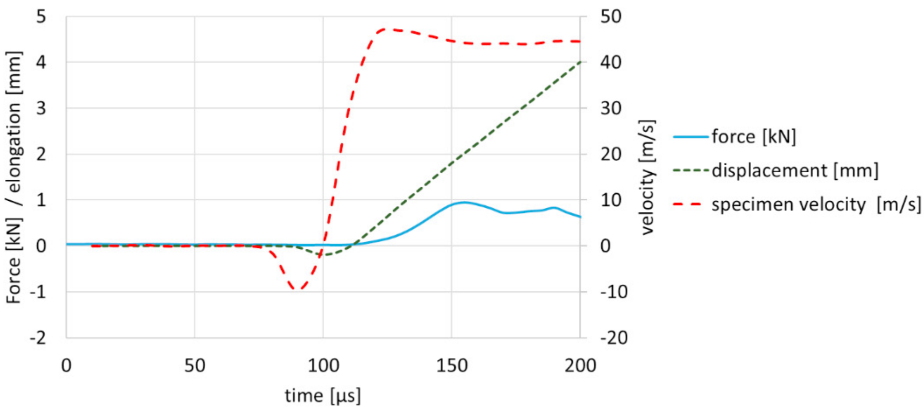


Fig. 3. Response of the force signal, the distance and the speed of the accelerated specimen end at a test speed of 40 m/s

It was also observed that the velocity of the sample tip is up to 20% higher than the velocity at the time of the impact of the towing arm. This results in a partially elastic impact, whose elastic part of the deformation of the impact partners is converted into a further acceleration of the specimen end after reaching the equal velocity. The tensile force of the specimen counteracts this. After reaching the apex this causes the velocity to drop until the specimen breaches. (Fig. 4)

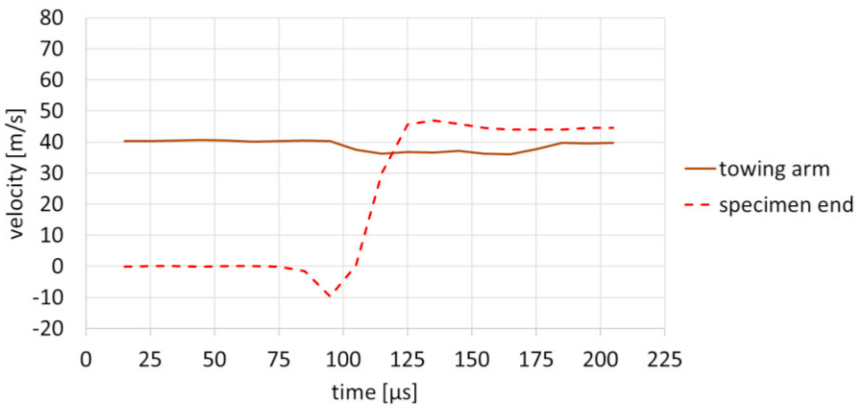


Fig. 4. Velocity vs. time curve of the towing arm and the accelerated specimen end at a test speed of 40 m/s

The observed behavior leads to the conclusion that the equilibrium requirement is a limiting element with regard to specimen length and velocity, since the distance to be completed by the strain wave increases directly with increasing specimen length and thus in the required time. A higher velocity, on the contrary, shortens the available time over the specimen length and the elongation at break. These correlations clearly show that above a certain speed-length ratio, equilibrium can no longer be expected. A further limitation is the acceleration process of the specimen, in which the specimen is already elongated but the initial condition of an almost constant velocity at the end of the specimen has not yet been reached. This process depends on the velocity of impact of the towing arm and the weight and material of the specimen tip. In the version under investigation, the yield point of the test specimen is not yet reached. If, however, higher speeds become necessary, materials are available with quenched and tempered steels that more than double possible loads at the same weight.

## 4. Conclusions and Outlook

A new tensile testing machine for high-performance fibers is described, that allows the application of strain rates of up to 267 $s^{-1}$ at the current state of the implementing process. It uses a rotating disc with an effective diameter of 800 mm as a source of defined movement, which provides an almost linear tensile test within the breaking elongations of the targeted materials. It was shown that the design of the specimen grips made it possible to transmit the velocities onto the specimen.

For analyzing of the measuring system, an analytical model was additionally set up and evaluated using SPICE® simulation tool, these results will be the subject of a further publication.

Based on the state of development achieved, various materials such as carbon fiber, glass fiber and aramid fiber, both dry and impregnated, are to be investigated.

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DFG Deutsche Forschungsgemeinschaft

## References

Al-Mosawe, A., Al-Mahaidi, R. and Zhao, X.-L. (2017), "Engineering properties of CFRP laminate under high strain rates", *Composite Structures*, Vol. 180, pp. 9–15.

Ashir, M., Nocke, A., Bulavinov, A., Pinchuk, R. and Cherif, C. (2018), "Influence of defined amount of voids on the mechanical properties of carbon fiber-reinforced plastics", *Polymer Composites*, Vol. 15 No. 2, p. 170.

Bleck, W., Frehn, A., Larour, P. and Steinbeck, G. (2004), "Untersuchungen zur Ermittlung der Dehnratenabhängigkeit von modernen Karosseriestählen", *Materialwissenschaft und Werkstofftechnik*, Vol. 35 No. 8, pp. 505–513.

Gizik, D., Metzner, C., Weimer, C. and Middendorf, P. (2017), *Heavy tow carbon fibers for aerospace applications, ADDITC*, Stuttgart.

Lindner, M., Vanselow, K., Gelbrich, S. and Kroll, L. (2018), "Fiber-Reinforced Polymers Based Rebar and Stirrup Reinforcing Concrete Structures", *Journal of Materials Science and Engineering A*, Vol. 8 No. 2.

Parry, D.J., Dixon, P.R., Hodson, S. and Al-Maliky, N. (1994), "Stress equilibrium effects within Hopkinson bar specimens", Journal de Physique IV (Proceedings), Vol. 04 C8, C8-107-C8-112.

Schuler, H., Mayrhofer, C. and Thoma, K. (2006), "Spall experiments for the measurement of the tensile strength and fracture energy of concrete at high strain rates", *International Journal of Impact Engineering*, Vol. 32 No. 10, pp. 1635–1650.

Unger, R., Schegner, P., Nocke, A. and Cherif, C. (2019), "Technological development of a yarn grip system for high-speed tensile testing of high-performance fibers", *AUTEX RESEARCH JOURNAL*, Vol. 19 No. 2.

Wang, Y., Zhou, Y., Xia, Y. and Jeelani, S. (2008), "Statistical Analysis on High Strain Rate Tensile Strength of T700 Carbon Fiber", in *Proceedings of the ASME International Mechanical Engineering Congress and Exposition 2007, Seattle, Washington, USA, November 11–15, 2007*, American Society of Mechanical Engineers, Fairfield, pp. 557–560.

Zhou, Y., Wang, Y., Jeelani, S. and Xia, Y. (2007), "Experimental Study on Tensile Behavior of Carbon Fiber and

Carbon Fiber Reinforced Aluminum at Different Strain Rate", *Applied Composite Materials*, Vol. 14 No. 1, pp. 17–31.