Materials Letters 355 (2024) 135498

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

# On the development of a high strain-rate tensile testing method for thin low-impedance materials

Georg Baumann [a,*,1], Caterina Czibula [b], Ulrich Hirn [b], Florian Feist [a]

[a] Vehicle Safety Institute (VSI), Graz University of Technology, Inffeldgasse 13/6, Graz, Styria 8010, Austria
[b] Institute of Bioproducts and Paper Technology(BPTI), Graz University of Technology, Inffeldgasse 23, Graz, Styria 8010, Austria

ARTICLE INFO

*Keywords:*
Hollow transmission bar
Low impedance
Numerical simulation
Paper
Split Hopkinson tension bar

ABSTRACT

This work deals with the high strain-rate characterization of paper under uniaxial tension using a Split Hopkinson test bench. An aluminum bar system featuring a highly sensitive hollow transmission bar was used. Paper tests were performed in a strain-rate range between approximately 60 $s^{-1}$ and 210 $s^{-1}$. The experimental tests showed that the breaking strength appears to decrease with increasing strain-rate. To verify these results, a digital twin of both the paper specimen and the entire test rig was created in an explicit Finite Element method environment. The numerical model was then used to perform a parameter study with different types of transmission bars. It was shown that the system is quite sensitive to additional masses caused by the specimen fixtures, as well as to drastic reductions in the cross section of the transmission bar. As a result, the transmitted measuring signal can be distorted and may need to be corrected using the digital twin.

## 1. Introduction

### 1.1. Background

When it comes to high strain-rate characterizations, the Split Hopkinson apparatus is a well-introduced experimental method. In order to characterize low impedance materials the testing facility needs some modifications in order to avoid poor signal-to-noise relations. One way is to replace the usual metal bars with bars made of polymers such as polycarbonate (PC) [1], polymethyl-methacrylate (PMMA) [2] or acrylic glass [3]. However, polymer bars have some disadvantages such as viscoelastic material behavior and relatively high sensitivity to ambient temperature, moisture and aging. Besides polymer-based systems another approach is the reduction of the cross-section of the metal bars, especially of the transmission bar. One such setup is described in [4] where a hollow transmission bar was used. In addition, a modified setup for high strain-rate tensile tests on thin metal foils can be found in [5]. This system is based on titanium and has progressively smaller cross-sections, starting with a 19 mm diameter striker bar, followed by a 14 mm diameter incidend bar and finally a 5 mm diameter transmission bar.

### 1.2. Motivation

Inspired by the use of small cross-section metal bars to characterize thin foil-like samples a similar setup was adopted for dynamic tensile tests on paper strips. Knowledge of the high strain-rate characteristics of paper is a vital information for the paper manufacturing process due to the high speeds in the continuous production. Besides the experimental tests, a digital twin of the specimen and of the entire test bench should be established in order to verify and assess the experimental results. The digital twin could further be used to find proper test configuration for individual test requirements, especially in new fields of application, such as the characterization of particularly low-impedance materials.

## 2. Materials and methods

### 2.1. Material

The paper material investigated is an industrially produced unbleached, unrefined, softwood Kraft pulp (Mondi Frantschach, Austria) made from a mixture of spruce and pine. Sheets were prepared according to ISO 5269–2 using a Rapid Köthen handsheet former. Fifteen in-plane handsheets with a surface weight of 160.1±1.8 $g/m^2$ were cut

* Corresponding author.
*E-mail address:* georg.baumann@tugraz.at (G. Baumann).
[1] Present address: Vehicle Safety Institute (VSI), Graz University of Technology, Inffeldgasse 13/6, Graz, Styria 8010, Austria.

https://doi.org/10.1016/j.matlet.2023.135498
Received 3 July 2023; Received in revised form 25 October 2023; Accepted 28 October 2023
Available online 30 October 2023

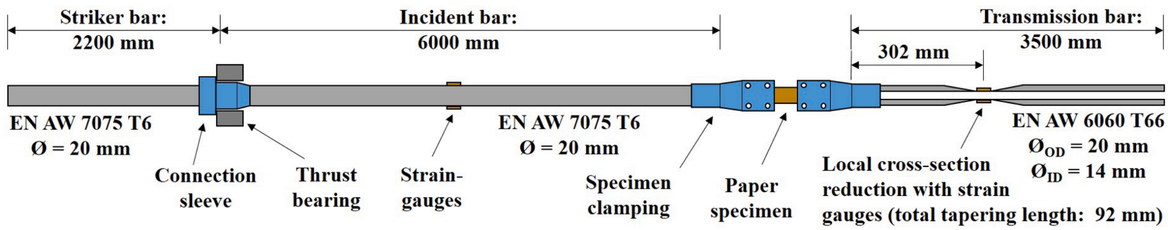



**Fig. 1.** Schematic longitudinal view of the Split Hopkinson test setup.

into a total of 30 test specimens with a format of 18.5×110 mm. In order to measure the deformation as well as the strain-distribution a millimeter scale and a speckle pattern was printed on the specimens (clamping length = 40 mm).

### 2.2. Experimental methods

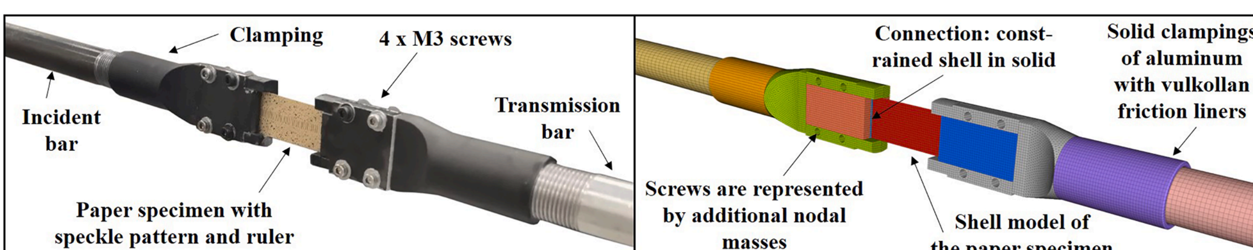
The Split Hopkinson test setup consists of two different types of bars. The striker and the incident bar are solid with a diameter of 20 mm. They are made out of EN AW 7075 T6 aluminum. In contrast, the transmitter bar, made from EN AW 6060 T66 aluminum, is hollow with an outer diameter of 20 mm and a wall thickness of 3 mm. To increase the compliance and, therefore, the sensitivity in the area of the strain gauges, the wall thickness is locally reduced to a residual wall thickness of 0.17 mm which results in a cross-section of only 7.96 mm$^2$. The wall thickness was determined through a micro-CT scan with a voxel size of 7.9 µm. For the tensile configuration described here, the striker and the incident bar are connected by a sleeve. Energy is built up by pre-stressing the striker bar and releasing it quickly by a mechanical release system described in [6]. The clampings are inspired by the design described in [7]. They are designed to provide a smooth successive transition from the circular bar shape to the flat specimen shape while keeping the cross-sectional area as constant as possible. The clampings are made from EN AW 7075 T6 aluminum. The friction linings are made out of an 1.5 mm thick elastomer (Vulkollan). The strain gauge signals were sampled at 2 MHz. In addition to the strain gauges at the bars, two contactless strain measurements of the specimen through DIC (Digital Image Correlation) techniques are included, employing an area camera (Phantom Veo 640) with 50 kfps and a line scan camera (Xposure AIT) with 500 kfps. A schematic overview of the experimental test setup is given in Fig. 1.

### 2.3. Numerical methods

In order to verify the results obtained from the experimental tests a digital twin of the specimen and of the whole test setup was created. The model was generated using the Finite Element Solver LS-Dyna (element size 1 mm). Bars, clampings and the paper specimen were modelled through a simple bilinear material model (MAT024). In case of the paper specimen, the bilinear material model was coupled with a GISSMO damage and failure model in order to map the failure strain obtained from the experiments on the digital twin. Two different strain-rates (62 s$^{-1}$ and 212 s$^{-1}$) were considered, with the lower strain-rate serving as the baseline for the material input. Strain-rate effects were intentionally disabled in the material model. Elastic energy is built up in the striker bar by displacing the bar-end by a prescribed motion. Next, unwanted vibrations were eliminated through global damping in the pre-stressing phase. Eventually, the stored elastic energy is quickly released, by eliminating the displacement constraint, which allows a pulse to form. Like in the physical tests, the strain-values of the incoming, reflected and transmitted pulse were evaluated at positions as in the physical counterpart. The numerical model allows to evaluate additional informations like the cross-sectional force in the specimen itself. This way the 'apparent' measurement (at the strain gauges) can be compared against the 'true' force (in the specimen). The simulation matrix covered – among other parameters, which are not presented in this paper – variations in (1) strain rate, and (2) the cross-sectional geometry of the transmitter bar. Two types of tubular bars with locally reduced wall-thicknesses and one all-solid bar with constant cross-section were considered. The first (hollow bar 0.17) had a residual wall thickness of 0.17 mm like in the experiment. With the second (hollow bar 1.0) the wall thickness was locally reduced to 1.0 mm. The solid bar had the same cross-section as the striker and incident bar. An overview of the specimen clamping in both the experiment and the simulation – including the material parameter settings of the FEM is given in Fig. 2.

## 3. Results and discussion

The results of the experiments as well as of the numerical study are summarized in Fig. 3. For clarity, only the averaged curve of the 15 individual experiments are displayed (black solid line). At low strain-rates, the stress signals at the specimen match well with the those of




| | |
|---|---|
| **Incident bar:** | **4471.16** |
| **Specimen:** | **8.88** |
| **Transmission bar (not tapered section):** | **2195.51** |
| **Transmission bar (tapered section):** | **109.08** |

| | Incident bar | Specimen | Transmission bar |
|---|---|---|---|
| **Young´s modulus:** | **72.35 GPa** | **4.00 GPa** | **69.56 GPa** |
| **Yield stress:** | **0.46 GPa** | **0.10 GPa** | **0.26 GPa** |
| **Tangent modulus:** | **0.70 GPa** | **0.50 GPa** | **0.70 GPa** |
| **Criticality strain:** | - | **2.5 %** | - |
| **Failure strain:** | - | **3.5 %** | - |

**Fig. 2.** Overview of the specimen clamping in the experiment (left) and in the simulation (right).

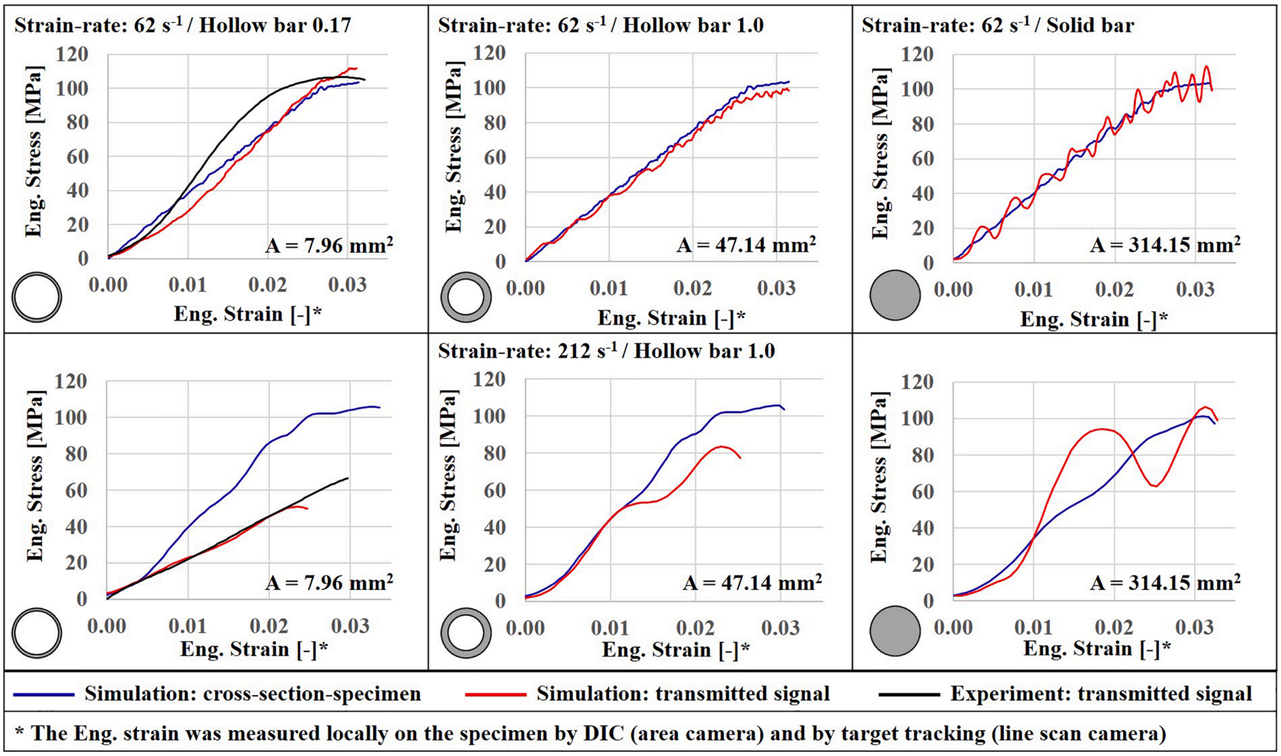



**Fig. 3.** Comparison of the experiment with the simulation including two strain-rates and three versions of transmission bars.

the transmitter bar. At high strain-rates, however, there is no good match between the transmitted signal (red-line) and the cross-sectional force (blue-line). With increasing sensitivity/tapering of the transmission bar, the amplitude and partially also the inclination of the transmitted signal decreases – compared to the cross-sectional force in the specimen. This is reason why, judging from the transmitted signals, strength and stiffness of the specimen seem to decrease with increasing strain-rate.

There are several potential factors likely having an impact on the transmitted signals. The first one is the effect of the mass resulting from the specimen clampings. With increasing strain-rate the accelerations, which are acting on these masses, are also increasing. This could lead to some form of pulse shaping. The second factor concerns the geometry of the transmission bars. The smaller the residual cross-section (or the larger the tapering) of the transmission bar, the more likely it is that a higher portion of the wave is reflected back instead of transmitted which further decreases the amplitude of the transmitted signal. Only in case of the solid bar the peak stress measured at the specimen cross-section and at the transmission bar are on the same level for both strain-rates. In the physical experiment, however, the signal-to-noise ratio would be too poor using this solid bar version.

## 4. Conclusions

An attempt was made to increase the sensitivity of a metal-bar based Split Hopkinson test bench by locally tapering a tubular transmitter bar. It was found that measurements at high-strain rates are not valid, as the transmitted pulse is modified by the mass of the clampings and parts of the wave are reflected at the taper. The digital twin allowed to compare the transmitted signal with the actual force in the specimen, which can deviate quite a lot. Furthermore, the numerical model would allow to calculate correction factors in order to make necessary scales on the experimentally obtained data, or to find more appropriate test setups that would result in less signal distortion.

## CRediT authorship contribution statement

**Georg Baumann:** Methodology, Validation, Investigation, Data curation, Writing – original draft, Visualization. **Caterina Czibula:** Methodology, Investigation, Writing – review & editing, Supervision. **Ulrich Hirn:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition. **Florian Feist:** Methodology, Writing – review & editing, Supervision, Project administration.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

The financial support by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Research Technology and Development is gratefully acknowledged. This study was funded by Christian Doppler Forschungsgesellschaft. C. C. acknowledges the Hertha Firnberg program (project no. T 1314-N) of the Austrian Science Fund (FWF). The authors would further like to acknowledge the use of HPC resources provided by the ZID and the use of the X-ray micro computed tomography infrastructure funded by the FFG at Graz University of Technology (Austria).

## References

[1] P. Jakkula, G.C. Ganzenmüller, S. Beisel, P. Rüthnick, S. Hiermaier, The Symmpact: A Direct-Impact Hopkinson Bar Setup Suitable for Investigating Dynamic Equilibrium in Low-Impedance Materials, Exp Mech 62 (2) (2021) 213–222.

[2] J. Janiszewski, W. Buzantowicz, P. Baranowski, Correction Procedure of Wave Signals for a Viscoelastic Split Hopkinson Pressure Bar, Problems of Mechatronics. Armament, Aviation, Safety Engineering 7, 1 (2016) 17–30.
[3] O. Sawas, N.S. Brar, R.A. Brockman, Dynamic characterization of compliant materials Using an All-polymeric Split Hopkinson Bar, Experimental Mechanics 38 (3) (1998) 204–210.
[4] W. Chen, B. Zhang, M.J. Forrestal, A split Hopkinson bar technique for low-impedance materials, Experimental Mechanics 39 (2) (1999) 81–85.
[5] C. Zhu, J. Xu, H. Yu, D. Shan, B. Guo, Size effect on the high strain rate micro/meso-tensile behaviors of pure titanium foil, Journal of Materials Research and Technology 11 (4) (2021) 2146–2159.
[6] G. Baumann, D. Niederkofler, C. Ellersdorfer, F. Feist, On the Development of a Release Mechanism for a Split Hopkinson Tension and Compression Bar, Materials 14 (2021) 24.
[7] G.C. Ganzenmüller, D. Plappert, A. Trippel, S. Hiermaier, A Split-Hopkinson Tension Bar study on the dynamic strength of basalt-fibre composites, Composites Part b: Engineering 171 (Suppl 5) (2019) 310–319.