



Original software publication

2BarG—A program to process split Hopkinson (Kolsky) bar test results

Tzvi Gershanik*, Itay Levin, Daniel Rittel

Materials Mechanics Center, Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, Haifa 3200003, Israel



ARTICLE INFO

Article history:

Received 1 March 2022

Received in revised form 12 April 2022

Accepted 14 April 2022

Keywords:

Split Hopkinson (Kolsky) Pressure Bar

Stress waves

Data processing

Signal analysis

ABSTRACT

2BarG is a program that analyzes Split Hopkinson (Kolsky) Pressure Bar experiments. It is Python-based and features several libraries that make processing fast, simple, and efficient with minimal operator's intervention. The program performs automatic identification of the incident, reflected and transmitted signals from the recorded experimental raw signals. The software reduces the data into stresses, strains, and velocities following the mandatory wave dispersion correction. A user-friendly and intuitive graphic interface allows for straightforward data reduction for various experimental specimens (standard or customized) and testing configurations (tension, compression, and shear).

© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Code metadata

Current code version	1.0
Permanent link to code/repository used of this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-22-00057
Legal Code License	N/A
Code versioning system used	git
Software code languages, tools, and services used	Python
Compilation requirements, operating environments & dependencies	Microsoft Windows, OS X, Linux
If available Link to developer documentation/manual	
Support email for questions	Greggersh1409@gmail.com

Software metadata

Current software version	1.0
Permanent link to executables of this version	https://rittel.group/downloads
Legal Software License	N/A
Computing platforms/Operating Systems	Microsoft Windows, OS X, Linux
Installation requirements & dependencies	None
If available, link to user manual - if formally published include a reference to the publication in the reference list	
Support email for questions	Greggersh1409@gmail.com

1. Motivation and significance

Hopkinson/Kolsky bar (SHPB) testing is the gold standard for the determination of the dynamic stress–strain properties of materials for strain rates ranging roughly from 10^3 – 10^4 s⁻¹. 2BarG performs the necessary data reduction from such experiments with minimum human intervention and maximum efficiency. The

following paragraph describes the experimental setup followed by the signal processing of the results.

The Kolsky bar (Fig. 1) consists of a set of two cylindrical steel (or other material) bars that are both free to move along their common axis [1]. Along this line, a shorter bar (referred to as the striker bar) can be accelerated to a certain velocity using for instance compressed air or other gases. Upon impact of the striker on the incident bar, an (incident) elastic stress wave (tension or compression) is generated into the incident bar, partly reflects into it (reflected) when it impinges upon the specimen, ultimately reaching the transmitted bar (transmitted). As shown in Fig. 1, the

* Corresponding author.

E-mail addresses: greggersh1409@gmail.com (Tzvi Gershanik), itaylevin2704@gmail.com (Itay Levin), merittel@technion.ac.il (Daniel Rittel).

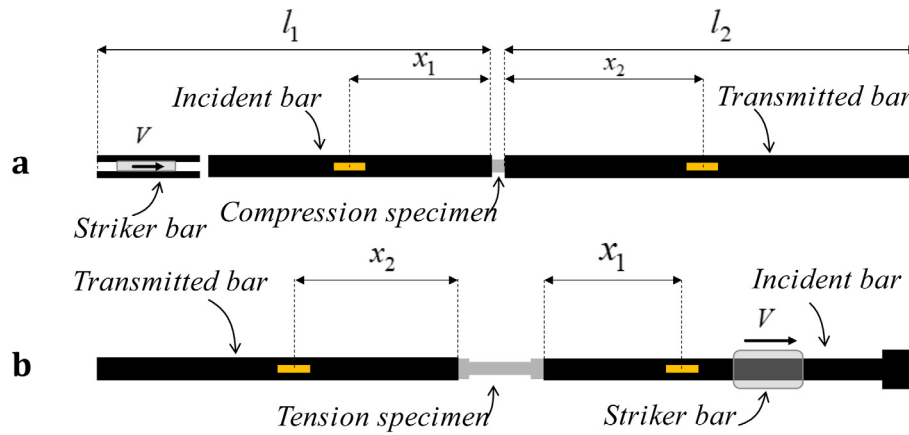


Fig. 1. (a) The SHPB compression configuration. (b) The SHPB tension configuration.

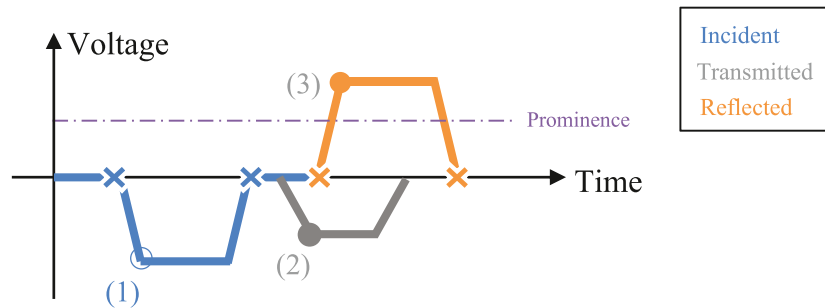


Fig. 2. Peak detection and cropping points of the experiment signals.

setup can be designed for tension or compression tests [2,3], as well as for shear tests [2,3] (not shown here).

For all devices (compression in Fig. 1a and tension in Fig. 1b), a pair of diametrically cemented strain gauges (to eliminate bending artifacts) on each bar (Fig. 1) record the three signals, namely incident, reflected and transmitted. The strain gauges are part of a Wheatstone bridge, as in any strain measurement setup. The SHPB can generate strain rates of about 10^3 – 10^4 s^{-1} .

The data reduction procedure of the recorded signals into stress, strain and velocities is detailed next.

Data processing of the Hopkinson/Kolsky bar can be somewhat cumbersome as it involves extensive data manipulation for the identification and time-shifting (synchronization) of the incident, reflected and transmitted signals, verification of the specimen equilibrium, and geometric dispersion correction [4] of those signals. Accordingly, various results are obtained, namely strains, strain rates, interfacial forces, displacements, and velocities. Based on this data, an accurate determination of the mechanical and failure properties of the investigated materials can be achieved, of the kind that can be used in constitutive modeling for structural design and failure analysis purposes [3,5].

2BarG is a sophisticated Python program that significantly simplifies and automates to a large extent the data reduction procedure. As such, it is the continuation and extensive rejuvenation of the in house TwoBarG program that has been used for years and was developed in Matlab environment. As of today, this software is obsolete in terms of programming and interface, as it performs somewhat slowly and requires constant updating to comply with new Matlab releases. But the main point is that extensive user intervention is required prior to and during processing, that slows down the processing of many experiments. By contrast, the new software described here is highly automated,

thus minimizing operator-related bias while speeding up data reduction.

Most available SHPB analysis software today [6–10] are somewhat complex, sometimes requiring extensive operator's involvement. Such a situation may result in an unsystematic approach that might bias the analysis outcome.

2BarG handles these shortcomings by providing a rather simple intuitive interface that anyone can operate – all that one needs is the experimental parameters and data files, and all is set for obtaining the final automated outcome. Since automatic peak detection is involved, which may need adjustments, two options are provided in the 'Settings' tab to improve the peak detection's performance on a specific signal: (1) a slider that reduces or increases the smoothing done on the signal to filter out the noise, and (2) an input bar to change the prominence percentage such as to better detect the signal's peak. These options make the data reduction process simple and repeatable.

Furthermore, 2BarG allows a quick save/ load of the experimental system's parameters, including default system properties, thus reducing the software's operation to simply loading the files and clicking "analyse".

2. Software description

2.1. Peak detection

A peak detection algorithm is used to find the incident, reflected and transmitted signals. A user defined prominence (defaults to 50%, dotted purple line in Fig. 2) sets a threshold for determining the maximum and minimum of the signals. According to the given prominence, 2BarG will seek each wave's first peak (see points (1), (2) and (3) in Fig. 2) and will then crop each signal in its starting and end points (see X marks in Fig. 2). This process results in the three desired cropped signals

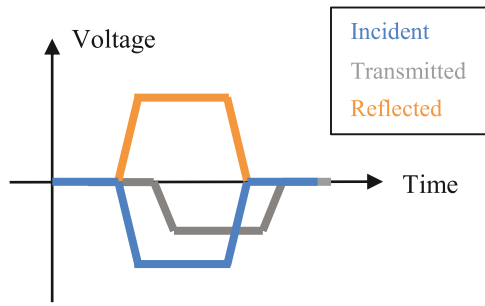


Fig. 3. Repositioning of the reflected and transmitted waves after auto correlation of the incident and reflected signals.

– Incident, transmitted and reflected. The cropping points are found simply by searching where the wave's amplitude changes its sign – before and after the wave's peak.

Since experimental signals are naturally noisy, a *Curve Smoothing* procedure is applied using the Savitzky–Golay filter to enhance the peak detection's performance. The applied smoothing is done by a user-defined parameter which can be found in the 'Settings' tab (Curve Smoothing). Formally this parameter is called the "Window Length" of the filter [11]. It is important to note that this is done on a copy of the data and there is no applied smoothing on the final analyzed outcome of the software.

2.2. auto-correlation

Once cropping has been applied, the reflected and transmitted waves are re-positioned in time to match the incident in the following manner: the reflected peak (point (3) in Fig. 2) is matched with the incident's peak (point (1) in Fig. 2)) using an auto correlation process, and the transmitted wave is moved backwards the same amount as the reflected wave. Fig. 3 presents a schematic illustration of the result.

2.3. Final calculations and report

The final step is the calculation of the needed quantities (stress, strain, forces, etc.). When calculation is finished, the results are exported into CSV files in each experiment's folder in the user-given path folder along with a text file containing the experiment's parameters. Unless set otherwise (in 'Settings' tab), a final report of the analysis will open in the user's browser and will be saved in the path folder as an HTML file. The report contains graphs produced with the analyzed data, the experiment parameters, and a calculated mean strain rate.

2.4. Software functionalities

In SHPB experiments, strain measurements are taken on the bars through which the wave propagates and not on the specimen itself (see the experimental setup in Fig. 1). Thus, a wave dispersion correction is required. According to [12], the strain at the specimen's location is given by:

$$\begin{aligned} \varepsilon(x_0 + \Delta x, t) &= \mathcal{F}^{-1} \left\{ \sum_{k=0}^{\infty} |\varepsilon_k(i\omega_k)| \cdot \exp \left[i \left(2\pi f_k \left(t - \frac{\Delta x}{c_k} \right) - \phi_k^{(0)} \right) \right] \right\} \end{aligned} \quad (1)$$

where $|\varepsilon_k(i\omega_k)|$, $\phi_k^{(0)}$, f_k , are the amplitude, phase and frequency of the k th Fourier component of the pulse at location x_0 , respectively, $\omega_k = 2\pi f_k$, \mathcal{F}^{-1} , is the notation for an inverse Fourier transform, i is the complex number $i = \sqrt{-1}$, c_k is the phase



Fig. 4. An example of arrangement of the files of 3 experiments.

velocity of each component and $\Delta x/c_k$ is the time it takes the k th Fourier component to travel the distance Δx .

$$\text{Define } \tilde{t} = t - \frac{\Delta x}{c_0}$$

$$\begin{aligned} \varepsilon(x_0 + \Delta x, t) &= \mathcal{F}^{-1} \left\{ \sum_{k=0}^{\infty} |\varepsilon_k(i\omega_k)| \cdot \exp \left[i \left(2\pi f_k \tilde{t} - \phi_k^{(0)} - \Delta \phi_k^{(\Delta x)} \right) \right] \right\} \end{aligned} \quad (2)$$

where

$$\Delta \phi_k^{(\Delta x)} = 2\pi f_k \Delta x \left(\frac{1}{c_k} - \frac{1}{c_0} \right) \quad (3)$$

is the increment of the j th Fourier component at location $x + \Delta x$, when the time is measured by the newly defined \tilde{t} . This increment is a result of the difference in phase velocities and is responsible for the dispersion of the pulse as it travels down the bar (when $c_j = c_0$ there is no dispersion). c_k is interpolated using Table 1 found in [13]. 2BarG calculates (Eq. (2)) swiftly using FFT (Fast Fourier Transform) algorithms and auto-correlates the incident and reflected waves as shown in Fig. 3.

According to [14] The specimen's displacement is given by

$$u_i = c_0 \int_0^t (\varepsilon_r - \varepsilon_i) d\tau \quad (4)$$

$$u_t = -c_0 \int_0^t \varepsilon_t d\tau \quad (5)$$

where c_0 is the one-dimensional longitudinal wave velocity of the bar ($c_0 = \sqrt{\rho/E}$), and ε_i , ε_r , ε_t are the incident, reflected and transmitted axial strains, respectively. Since the difference between the incident and reflected waves ($\varepsilon_r - \varepsilon_i$) is required for integration (Eq. (4)), auto correlating them reduces the noise resulting from the sum of the two signals and their natural high frequency oscillations (Eq. (5)).

3. Illustrative examples

3.1. Input file architecture

The file name should be $X\#\text{filetype}$, where X is a name that does not include numbers, and $\#$ is a running number. *Consecutive numbering* is a necessity. The numbering method is up to the user's preference. Once 2BarG has recognized the files properly, the files will be arranged automatically and conveniently into experiment folders (see Fig. 4).

Files should come in even pairs otherwise the analysis will not proceed correctly due to a failure of the program to identify the

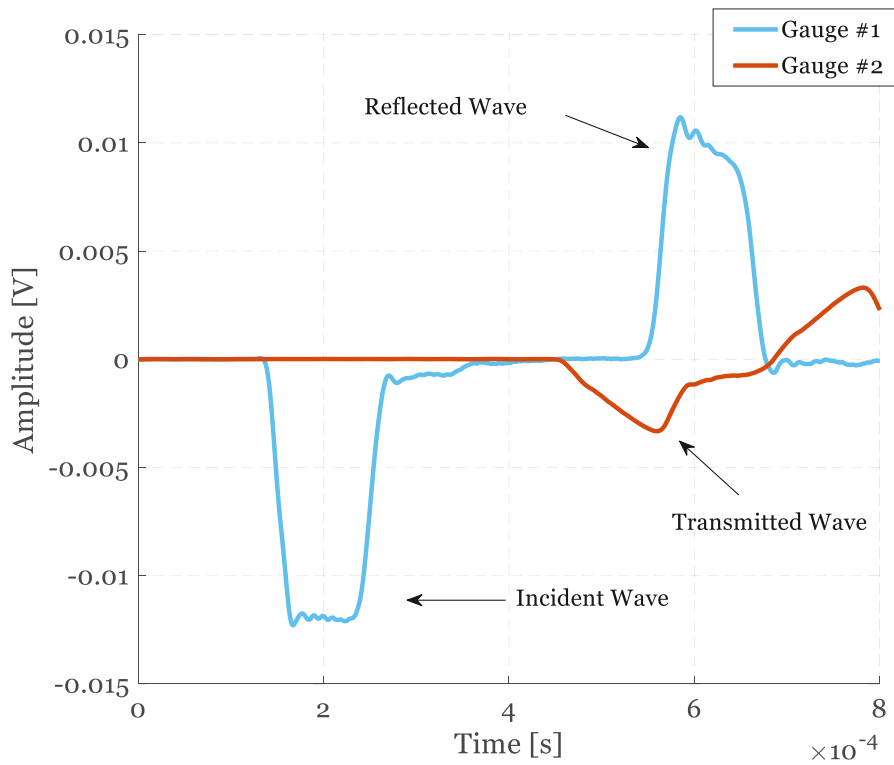


Fig. 5. Example of experimental incident, reflected and transmitted signals, Titanium Grade 2 - Compression experiment.

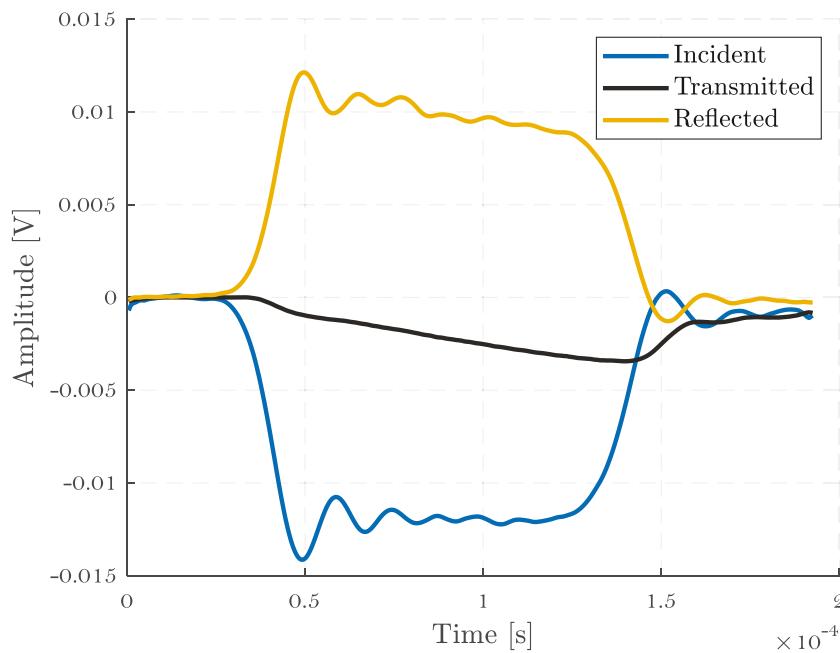


Fig. 6. Incident, transmitted and reflected waves after dispersion correction and auto-correlated alignment, calculated by 2BarG for Titanium grade 2 - Compression experiment.

files. 2BarG accepts files in the following formats: CSV/ xlsx/ ASCII (txt)/ FLT/ WFT.

3.2. Analyzed results example

Typical analyzed results for a Titanium Grade 2 SHPB compression experiment are shown next, in Figs. 5–8.

4. Impact

2BarG provides the way to a simplified analysis of Split Hopkinson pressure bar experiments, helping users to acquire the desired data swiftly through a modern and intuitive interface, with minimal user involvement. It is expected that 2BarG will be widely adopted by the Experimental Dynamics community,

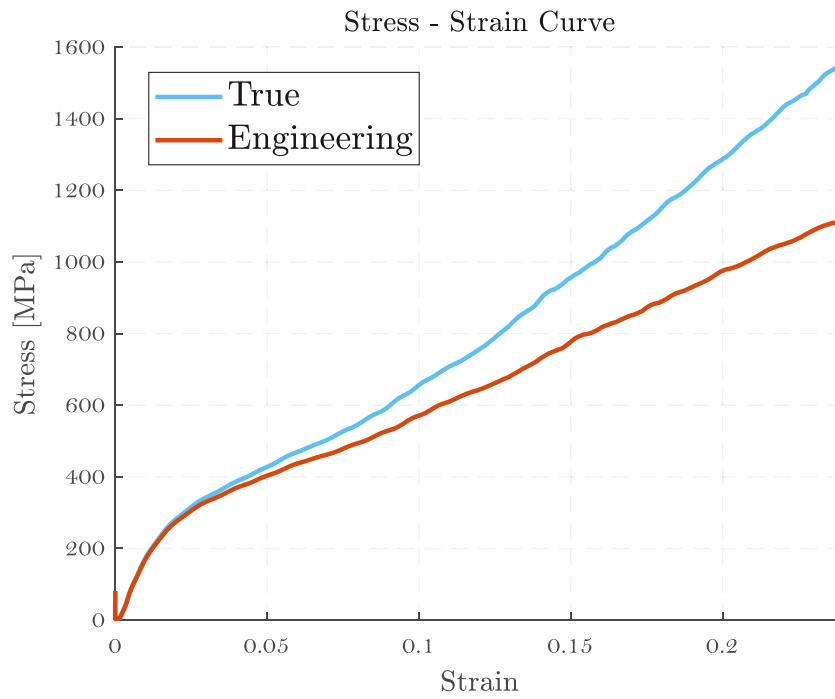


Fig. 7. Stress–Strain (true and engineering) flow curves of Titanium grade 2 as an example, calculated by 2BarG-SHPB Compression experiment.

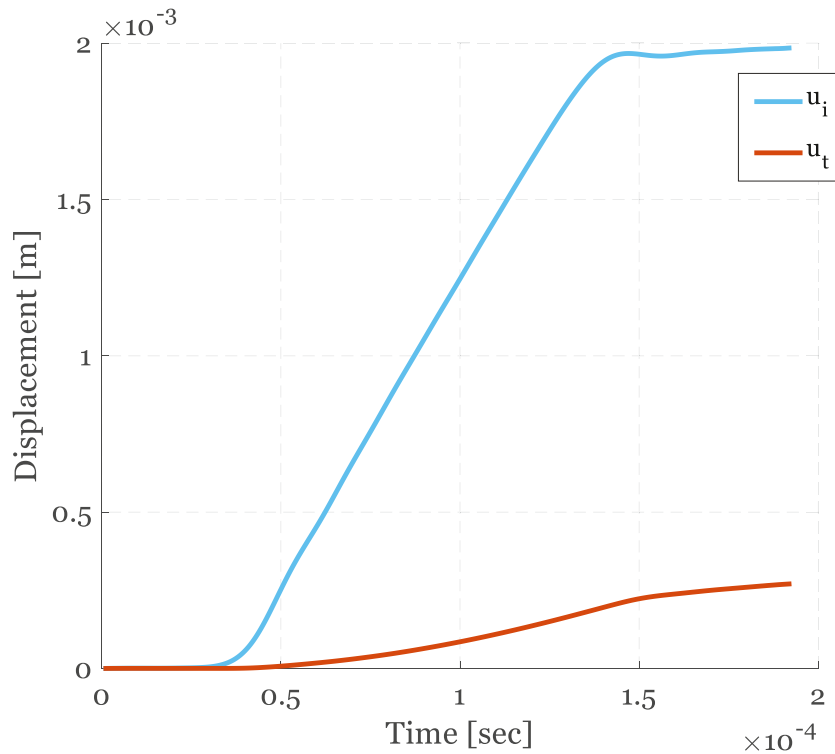


Fig. 8. Displacement vs. time of Titanium grade 2 as an example, calculated by 2BarG-SHPB Compression experiment.

thereby becoming sort of a standardized platform through which results can be compared, including in the form of round robins, for which a unified program was missing.

5. Conclusions

2BarG is a simple and intuitive program that allows for easy, fast and reliable processing of Split Hopkinson (Kolsky) pressure bar results of all kinds, including non-standard specimens. It is

hoped that 2BarG will be adopted as a standard platform for dynamic testing of materials.

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.

Acknowledgments

Useful discussions with Dr. S. Chen are acknowledged.

Appendix. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.softx.2022.101093>.

References

- [1] Landon and quinney. In: Experiments with the Hopkinson pressure bar. 1923, p. 622–43.
- [2] Meyers Ma. Dynamic behavior of materials. John Wiley & Sons, Inc; 1994.
- [3] Springer handbook of experimental solid mechanics. Springer US; 2008, <http://dx.doi.org/10.1007/978-0-387-30877-7>.
- [4] Pochhammer L. Ueber die Fortpflanzungsgeschwindigkeiten kleiner Schwingungen in einem unbegrenzten isotropen Kreiszylinder. *J Reine Angew Math* 1876;1876:324–36.
- [5] Jiang F, Vecchio KS. Hopkinson bar loaded fracture experimental technique: A critical review of dynamic fracture toughness tests. *Appl Mech Rev* 2009;62:1–39.
- [6] Kirby SP, Ejenavi JO, Matin P. Designing a data acquisition system for a split hopkinson pressure bar. In: ASEE annu. conf. expo. conf. proc. 122nd ASEE. 2015.
- [7] Alves M. A software for a dual split hopkinson bar machine. In: Congr. nac. eng. mecâ. 2014.
- [8] Whitemont E. The NIST kolsky bar data processing system society for experimental mechanics annual conference 2005. In: Soc. exp. mech. annu. conf. 2005.
- [9] Francis DK others. Split hopkinson pressure bar graphical analysis tool. *Exp Mech* 2017;57:179–83.
- [10] Lee SH, Tuazon B, Shin HS. Construction of data acquisition/processing system for precise measurement in split hopkinson pressure bar test. *Appl Mech Mater* 2014;566:554–9.
- [11] `scipy.signal.savgol_filter` — SciPy v1.8.0 Manual https://docs.scipy.org/doc/scipy/reference/generated/scipy.signal.savgol_filter.html.
- [12] Lifshitz JM, Leber H. Pergamon data processing in the split hopkinson. *Int J Impact Engng* 1994;15:723–33.
- [13] Bancroft D. The velocity of longitudinal waves in cylindrical bars. *Phys Rev* 1941;51:588–93.
- [14] Sun C. Testing methods for dynamic interlaminar fracture toughness of polymeric composites. *Delamination Behav Compos* 2008. <http://dx.doi.org/10.1201/9781439832677.ch4>.