

Operation of Bending Machine BM2

User Manual

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1. Introduction and general information

The bending machine is designed mainly for bending tests with stable crack advance (Fig. 1) and enables the measurement of R-curves. For this, the machine has a very high stiffness based on a solid and compact frame. This ensures that under loading the machine does not absorb much mechanical energy due to elastic deformation. Based on FEM analysis, the former student Henning Krohn (Appendix C) determined that the most critical points concerning high stiffness are the points of line contact or point contact. Thus, the whole load cell and also the support rollers having line contacts are made of hard metal.

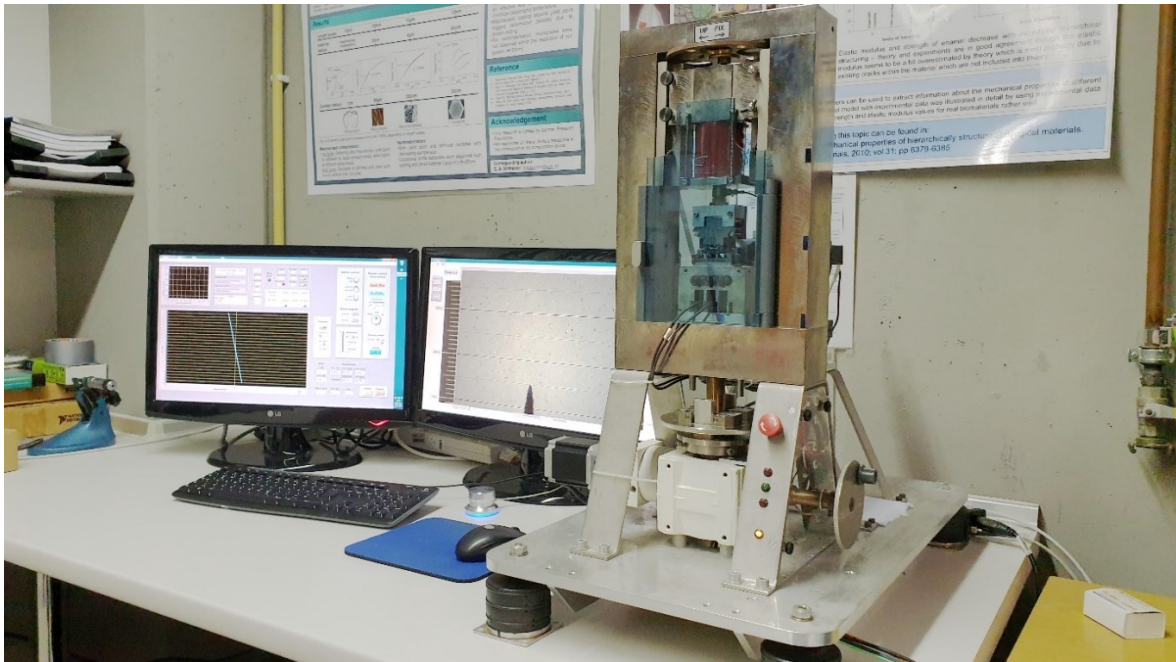


Figure 1: Bending machine BM2 (with adjusted and 45-mm-long bending sample). The CCD camera with the optics for crack length determination is positioned on the back side of the device.

A new feature is the automatic computer control of stable crack advance (patent 2014, reference number: **DE 10 2009 034 188 B4**, 2014.09.25). As soon as the crack starts to grow, the machine partially unloads by a predefined amount. The method is described in [1].

As in other testing devices, stable crack advance is obtained by iterative and partial unloading of the sample. After the unloading, the crack length is determined and the sample is again loaded for another short distance of crack advance. Concerning R-curve measurements, the bending machine BM2 has some advantages compared to other conventional testing machines:

1. The control of stable crack growth is not achieved by microscopic inspection of the moving crack tip and manual unloading, but automatically by the computer program. Crack advance means that the compliance of the sample slightly increases and this is detected by continuously measuring the slope in the load-displacement diagram (force-displacement diagram) by linear regression. A partial unloading by the computer follows as soon as the current slope undershoots a predefined threshold.

2. In 4-point bending, the crack length is not measured optically but on the basis of the compliance of the sample. For additional test purposes, the crack length is determined optically from time to time with microscopic optics. The principle of this compliance method is not new, but the realization with this kind of bending tests is.
3. Normally, the crack front is not straight but slightly curved. Within the sample, the crack propagates further than on the surfaces of the sample. The reason is that, at the crack front, there are mainly plane strain conditions within the sample, whereas on the sample's surfaces there is plane stress. One consequence is that the fracture toughness, calculated using the optical crack length, is slightly too low, and therefore, lower than the fracture toughness, calculated using the compliance method. Thus, if the crack is detected for the first time on the surface (first unloading by visual observation), the crack would have already grown within the specimen, meaning the first unloading could be too late, causing an unstable fracture. This is not the case when using the compliance method because the computer "feels" crack growth inside the specimen without any optical crack advance.
4. Another advantage is that the sample preparation of bending samples is much easier than producing, e.g., compact tension specimens (CT). Some data corrections are necessary, partly depending on the kind of material. These refer to the load drift, the dead weight of upper support, and optionally to corrections due to inelastic nonlinear material behavior. However, the correction required is usually small for short crack lengths, which are most important because they present the initial increase in the R-curve. Thus, regardless of the different corrections, if specimens of different materials are tested under precisely the same conditions, it is possible to adequately compare these different materials.
5. Furthermore, from a single reloading following the unloading of a sample, information about subcritical crack growth can be derived. At a constant loading rate, this phenomenon increases with increasing crack lengths. The corresponding evaluation procedure is described in Refs. [2] and [3].

Additional technical information is given in Appendix A (main equations), Appendix B (summary of load cell dimensions), and Appendix C (compilation of student works).

2. Description of the machine

The main parts of the work station are the bending machine, a computer with two monitors, and an acoustic rack containing the computer and the entire electronics (see Figs. 2–5).

Different kinds of load cell geometries exist. An example having support distances of 20 mm and 40 mm and two position encoders is provided in Fig. 7. This loading geometry is necessary if the crack length is determined by means of the compliance method. A summary of all

possible load cells with individual load geometries is provided in Appendix B. For the sake of completeness, this table also contains load cell dimensions of the first prototype of bending machine (BM1). A general overview of the bending machine BM2 is given in Fig. 2.

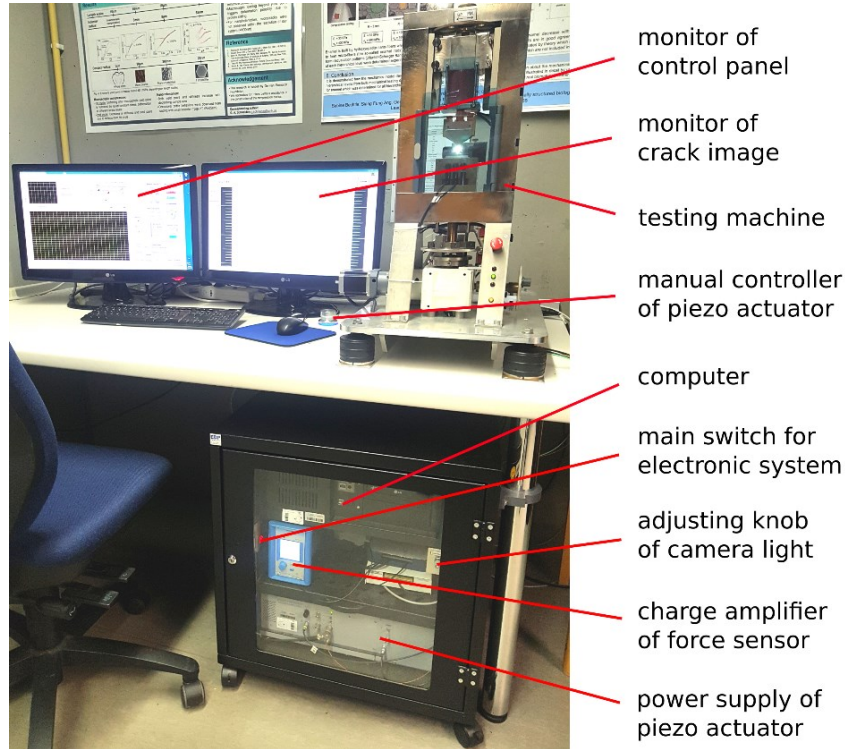


Figure 2: Work station for bending experiments and especially R-curve measurements.

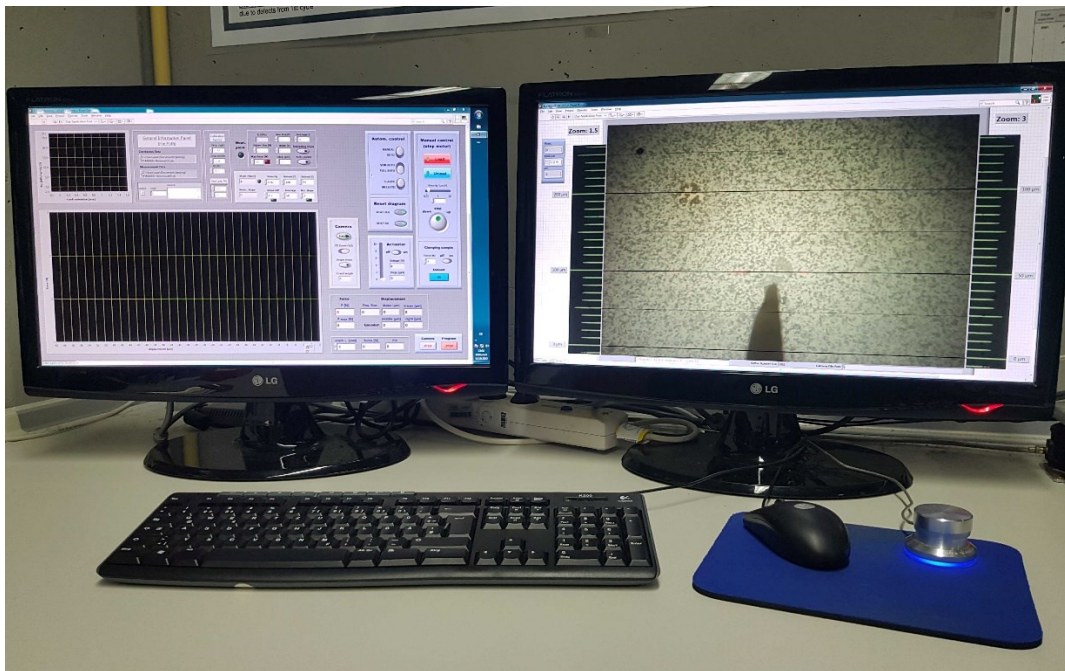


Figure 3: Working area with control panel on the left and monitor with microscopic image on the right. The round aluminum control knob on the mouse pad allows for the manual adjustment of the voltage (displacement) of the piezo actuator. (Note: This currently does not work due to a software problem with the driver of this device; however, until now, it's use has not been required.)

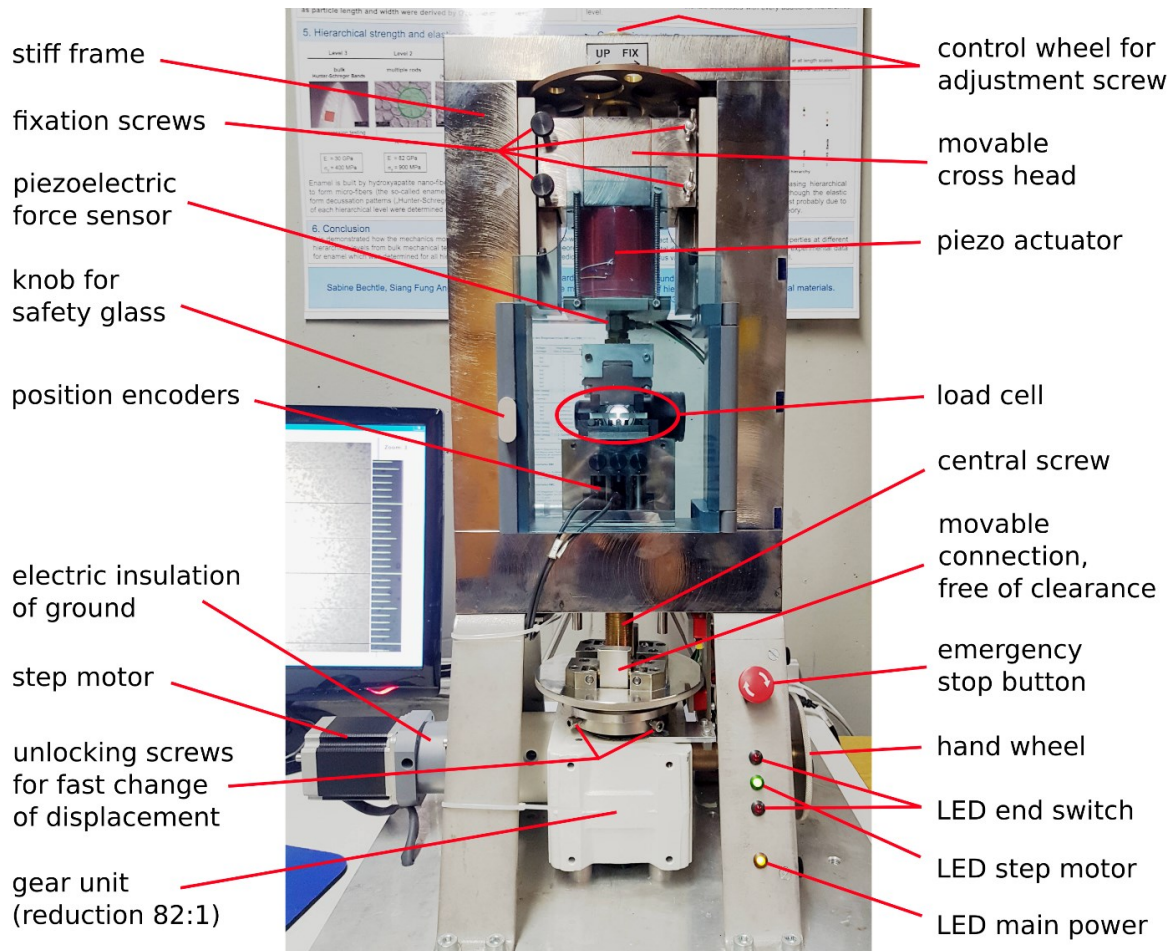


Figure 4: Mechanical setup of the bending machine BM2 with its main components.

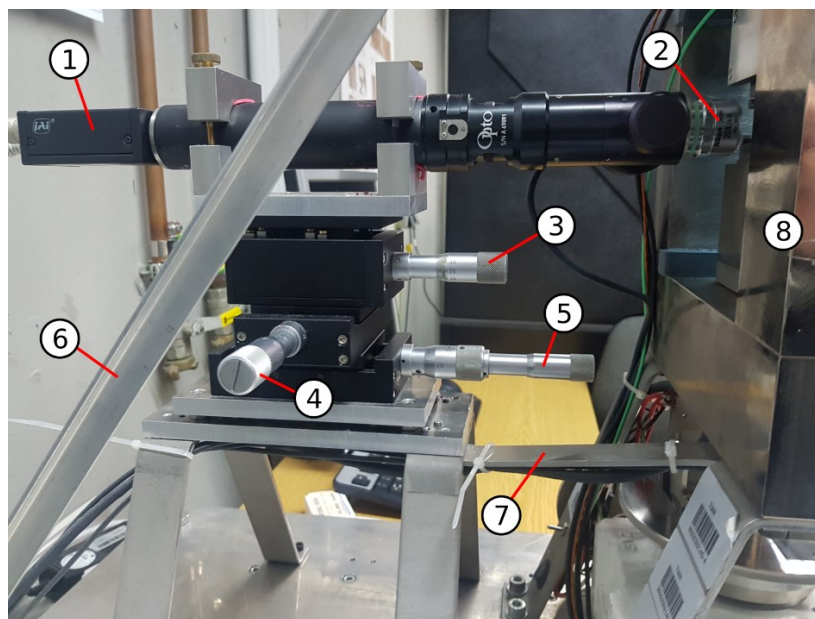
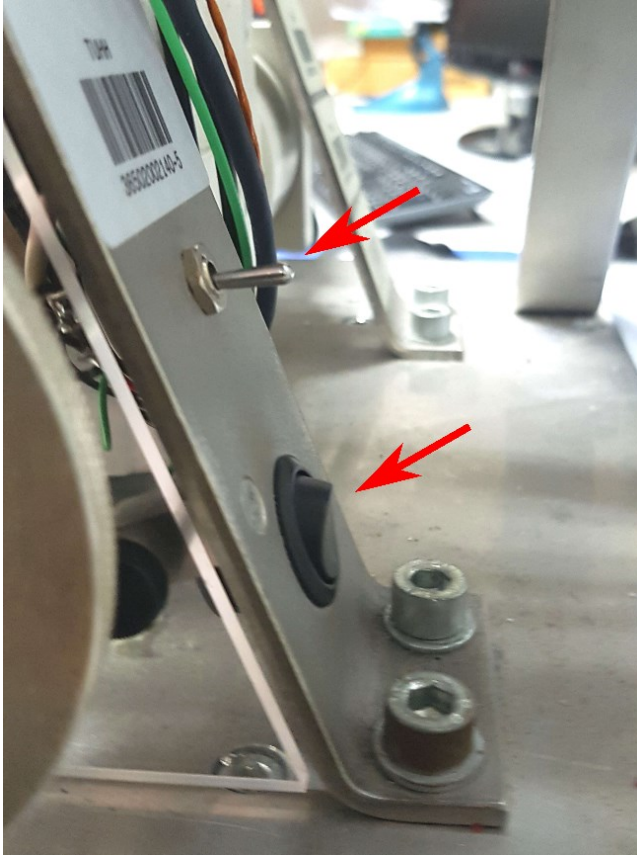


Figure 5: Microscope with CCD camera and 3D-positioning table on the back side of the bending machine. The individual parts are: (1): CCD camera; (2): long-distance zoom optics of microscope (main magnification 400x); (3): adjusting knob for vertical position of camera; (4): adjusting knob for horizontal position of camera; (5): adjusting knob for focus; (6), (7): rods for stiffening the machine, especially for image stabilization; (8): stiff main frame. Rubber bands in the clamping mechanism of the camera tube stabilize the microscopic image with respect to vibrations due to the step motor.



The load sensor is fixed with two screws (not visible) with a defined momentum of 1 Nm. Thus, the load sensor should not be dismantled if not necessary.

On the back side of the testing machine, there are two switches (Fig. 6). The lower one is for the step motor and the upper one for the sound of the end switches. The upper one should always be switched to on (down position) so that the sound is enabled. (The end switches are red, each with a yellow button, as shown in Fig. 4.)

Figure 6: The two switches on the back side of the testing machine. The lower one is for the step motor and the upper one for the acoustic signal of the end switches.

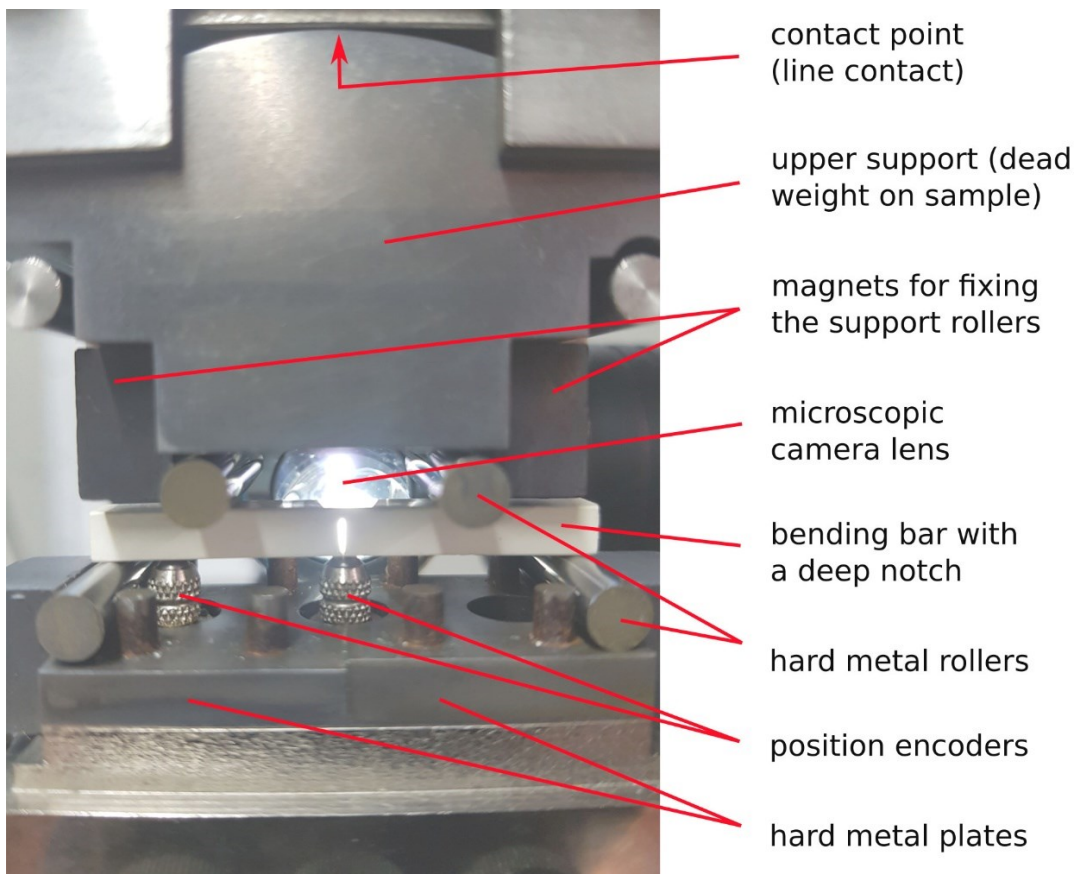


Figure 7: 4PB load cell of the bending machine BM2 with support distances of 20 mm and 40 mm.

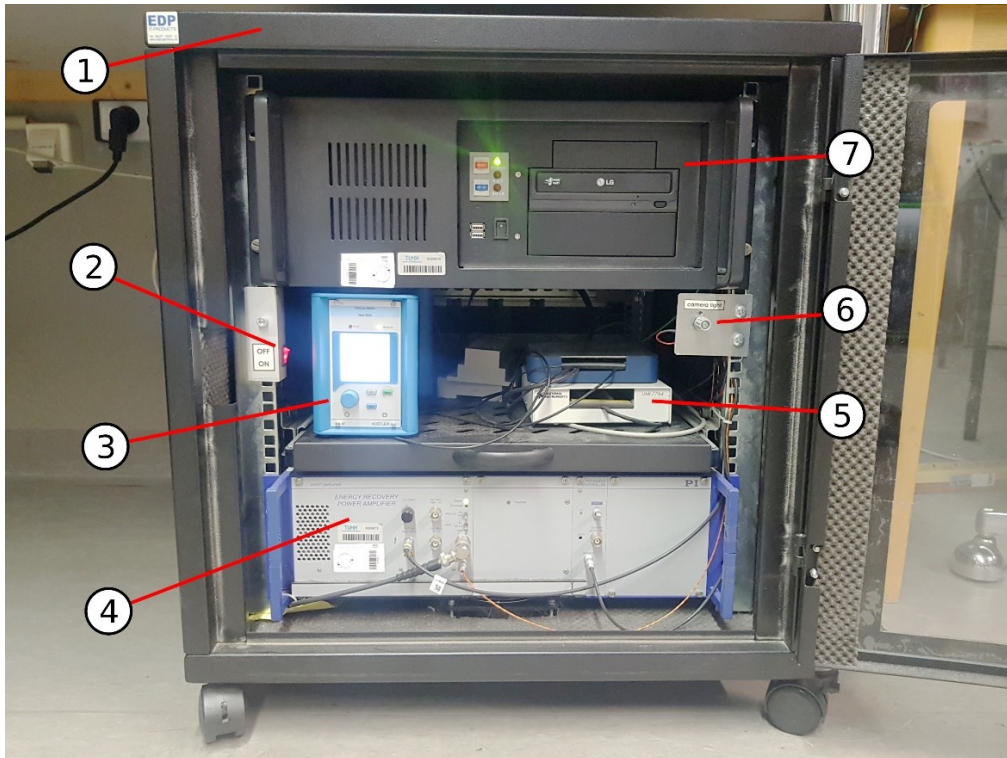


Figure 8: Open front of the acoustic rack. The main features are: (1): electronic rack, acoustically (and thus thermally) insulated; (2): main power switch for the electronics (except the computer); (3): charge amplifier (Kistler) for the load sensor; (4): power supply for the piezoelectric actuator with a linearized working characteristic; (5): special electronic box from National Instruments; (6): rotary switch for adjusting the brightness of the inline video illumination; (7): computer for data acquisition.

Figure 8 shows the opened front of the acoustic rack. When the electronics and the computer are switched on and the front door is closed, it is very important to ensure that the ventilators (Fig. 9) are working. If they are not working, the electronics, and particularly the computer, will overheat.

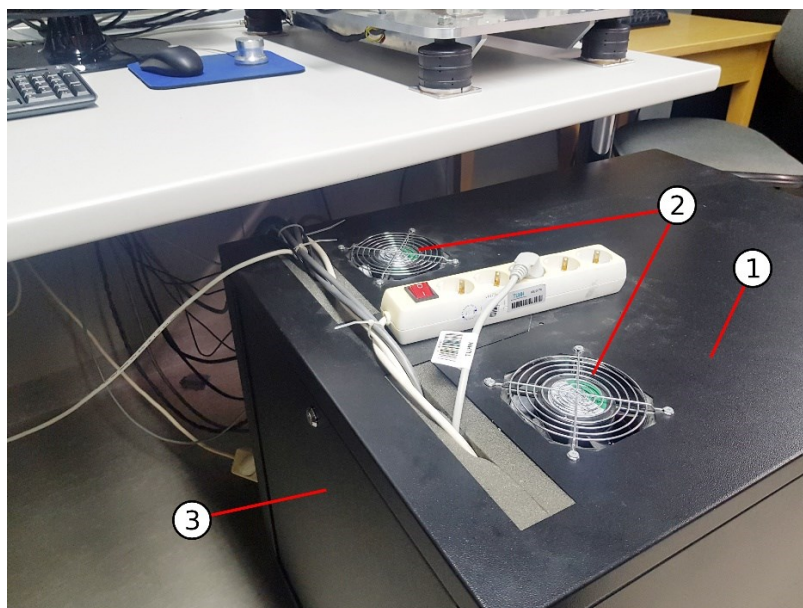


Figure 9: Top surface of the rotated acoustic rack (1) with two ventilators (2). The back door (3) is closed.

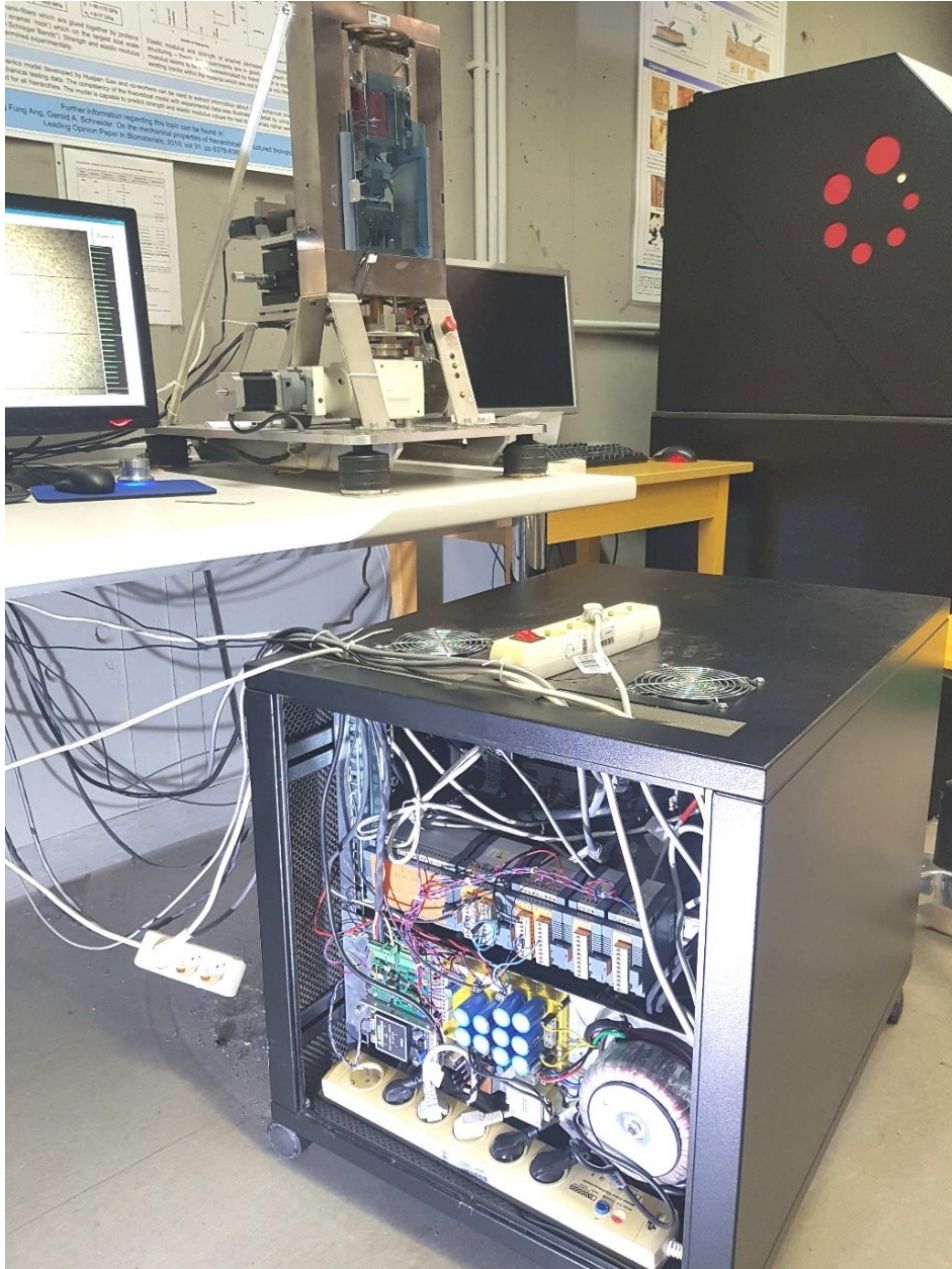


Figure 10: The acoustic rack for the electronics must be rotated around the table leg in order to access the back side.

In order to access the electronics from the back side, the rollers of the rack must be unlocked for the rack to be rotated around the table leg, where the rack is fixed (see Fig. 10). Cables should be handled with care. The key for the front door of the rack can also be used for the back door. An overview of the electronics on the back side is given in Fig. 11.

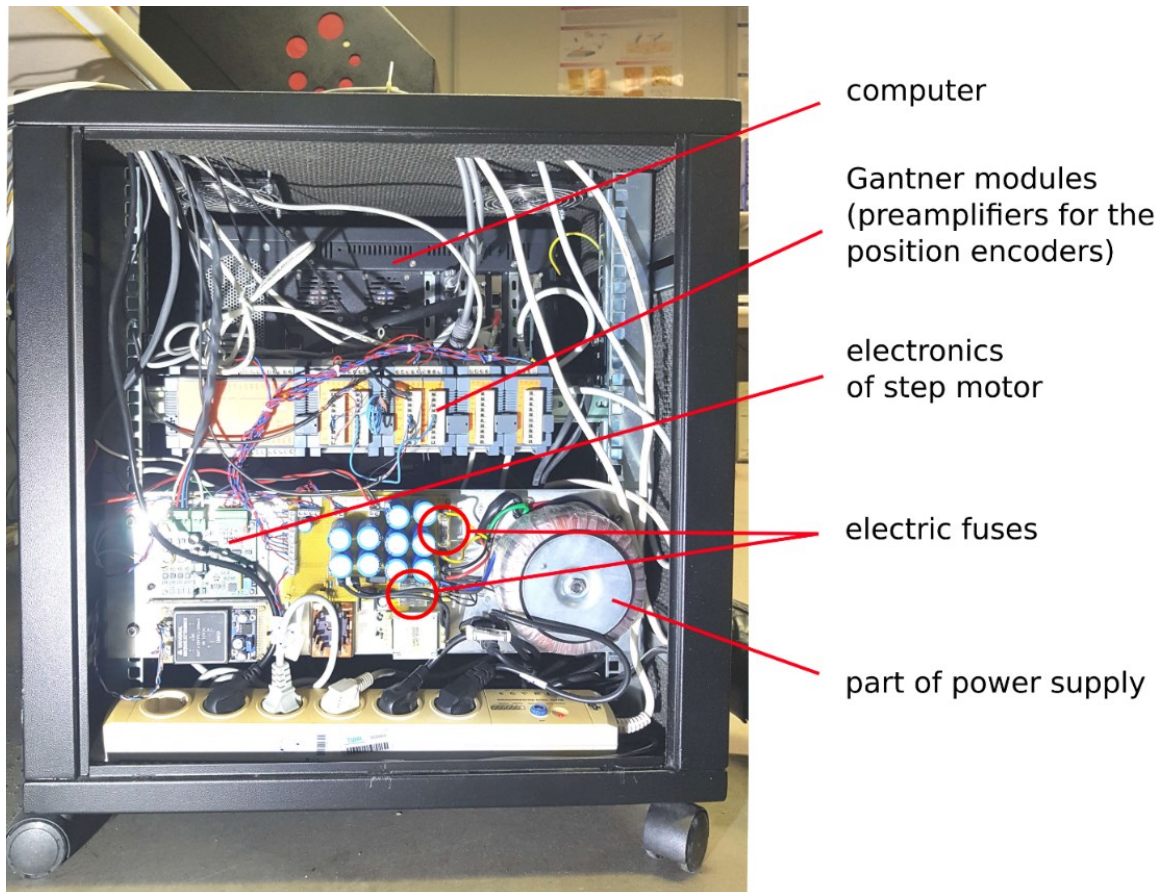


Figure 11: Electronics at the back side of the electronic rack.

If one of either position encoders is not giving a signal, it is possible that one of the fuses is defective and needs to be replaced (see Fig. 11). The master slave plug board on the base of the rack provides electric power for all electronics, except the computer. This enables all electronic devices to be switched on with one switch at the front of the rack. As previously mentioned, ensure that the ventilators at the upper surface of the rack (Fig. 9) are working when the main switch is on, otherwise the electronic assembly in the rack, and particularly the computer, will become too hot and could potentially be damaged. Because the rack is acoustically insulated, and thus also thermally insulated, a fire outbreak could also be possible. A third ventilator is positioned in the floor plate of the rack.

Figure 12 shows the upper parts of the load cell that need to be mounted if 4-point bending is to be used, as well as the parts of the compression load cell. In most cases, the hard metal support (1) should be used because of its high stiffness (Young's modulus > 500 GPa). If a fragile material, e.g., glass, is to be measured, the steel (VA) support (2) should be used, because it means less dead weight on the sample

The dead weight correction includes the weight of the upper load cell support as well as the position encoders, which act as negative dead weight. The weight of the upper hard metal support, including magnets and rollers (see (1) in Fig. 12), is 3.9 N, and that of the upper steel support is 2.2 N, accordingly. The position encoders act against this dead weight with ca. 0.8 N. Thus, the resulting dead weights are 3.1 N for the hard metal support and 1.4 N for the steel support.

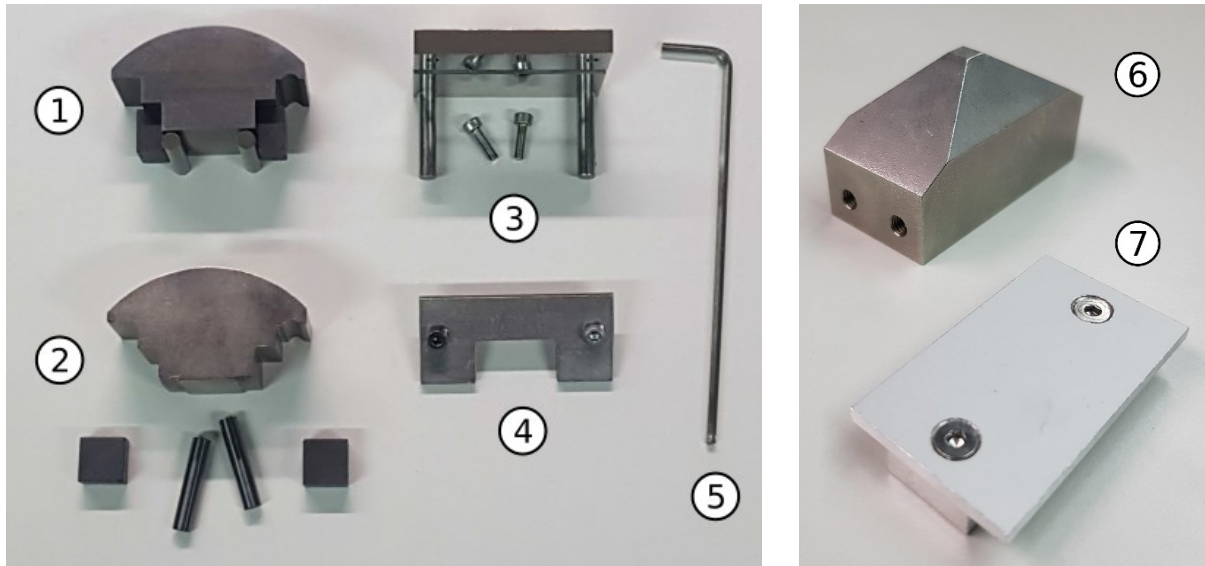


Figure 12: Upper parts of the load cell for 4-point bending and upper and lower parts for the compression test: (1): hard metal support with mounted hard metal rollers and magnets; (2): steel support (VA) with separate rollers and magnets; (3): support plate for the back side of the load cell; (4): Plate for the front of the load cell; (5): hex wrench for the screws; (6): upper part of compression load cell; (7): lower part of compression load cell.

Figure 13 presents some templates for accurately adjusting the position of the upper support and of the bend specimen.

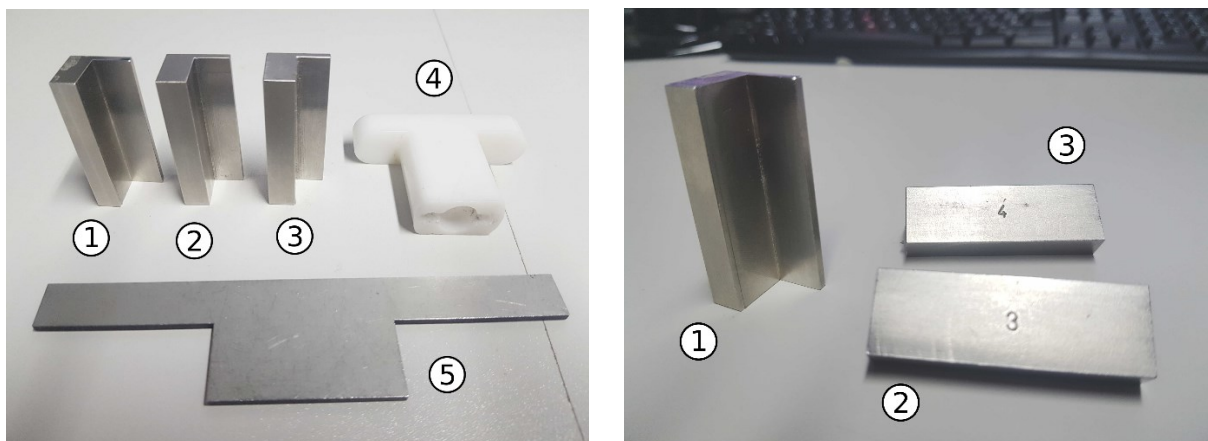


Figure 13: (1)–(3) are templates for adjusting the bending bar in the depth direction when it is placed on the lower support rollers – the number engraved on each template (image on right) specifies the width of the specimen, e.g., “3” means a width of 3 mm; (4) is a key for facilitating the fastening of the two wing screws on the right of the cross head; (5) is used to adjust the depth position of the upper support of the load cell.

The numbers on the templates (1)–(3) indicate the width of the bending bars in mm. Template (5) is used for adjusting the upper support, and the key (4) allows the wing screws to be more easily fixed.

3. Starting a measurement

3.1 Checklist for R-curve measurements (BM2)

The following brief description was originally created by the former student Marcelo Barros and has subsequently been slightly extended. *Before beginning:* Measure the height, width (micrometer screw), and notch depth (microscope) of the sample. A good notch tip radius is less than 10 μm .

1. Turn on the electronics and then the PC. It is recommended that the electronics be switched on \approx 2h before testing in order to minimize any electronic drift.
2. Password in PC: "user"; select the file "4 Point bending - 151215 Jannik" on the desktop.
3. Press the *green button* in the charge amplifier (blue box). The green light must be on.
4. Put the sample in the device. Adjust the height in relation to the sample and fix the butterflies. Check that the upper support (move metal plate) and the sample are properly placed.
5. Press the RUN button (arrow) in LabView (Fig. 15). ►
6. Set the sample parameters, name files. Ensure correct setting: *Pos Encoder ON or OFF, Mode Selector 3-Point or 4-Point* (Fig. 16).

Adjust sample and parameters

7. Reset the blue box (press the green button, wait approx. three seconds, and press again).
8. Record the force value (1.2 N) for your reference and later subtract it from the final values. If the upper 4PB hard metal support is used, the dead weight is 3.1 N.
9. Switch step motor ON with the lower button on the back side of the bending device. The green LED at the front will turn on.
10. *Clamping sample:* Set force to 2–4 N and press ON for clamping the sample (Fig. 17). The green LED of the charge amplifier must be on! When clamping is finished, switch off the clamping button.
11. Adjust the optical microscope distance, height, and light intensity; focus on the notch tip.
12. Set encoder(s) between -50 and -10 μm (if they are being used).
13. Remove settling effects by gently tapping the support with the template; see (5) in Fig. 13. This is done, when the force of a few Newton does not change any more.
14. *Reset diagram:* Press both buttons (Fig. 17) – slightly change force – press RESET RED.
15. Unload the sample down to "zero" force. This means that the force shows only the dead weight and would not change anymore when further unloading.
16. Reset green button in the blue box again (2x).
17. Set *Average* and *Average 2* (two fields, Fig. 19) to 25 points or other value.
18. Select INELASTIC and, e.g., SEMI-AUTO for optical crack length determination.
19. Always adjust *N. E. Slope* to a slightly lower value than the current slope.

Start of measurement

20. When everything is ready, stop program and restart it again.
21. *Average* points to 25 (2x) and press the corresponding button to INELASTIC.
22. Measure 3–5 points by pressing the middle mouse button (wheel).

23. Select “Auto points” ON for the first ramp and for force adjustment; OFF during test.
24. Vary force (until slope is stable) and activate AUTO for running the test.

During the test

25. By controlling *N. E. Slope*, make sure that the sensitivity of the machine for the automatic unloading cycles is properly defined. Take photos during the test with the “foto” button (only when no pop-up window is open).
26. For the subsequent drift correction, unload completely every 20 to 30 minutes (after unloading click the middle mouse button 3x). It might be useful to switch on “Auto points” during unloading and reloading.

End of measurement

27. Unload completely; press mouse wheel 3x.
28. Take a screen shot and save it (e.g., to LibreOffice Impress), then press “Program STOP” button.
29. Store your data files, photos, and screen shots in a personal folder.
30. Remove the sample, switch off the electronics, and shut down the computer. Never update LabView 2011 because this is the valid version. Leave the working place clean.

3.2 Adjusting the position encoders

When starting the program for the bending machine BM2, a critical point is the adjustment of the position encoders (see point 12 above). The problem is that the active range of the position encoders is only ca. $\pm 58 \mu\text{m}$, which is a range of ca. $116 \mu\text{m}$. It is almost impossible to find this range by moving the position encoders directly by hand. For this, we use a hexagonal wrench of size 6 or 8, as shown in Fig. 14. Before doing this, the specimen must be correctly placed and slightly clamped with a force of a few Newton so that it cannot move if one of the position encoders touches the sample.

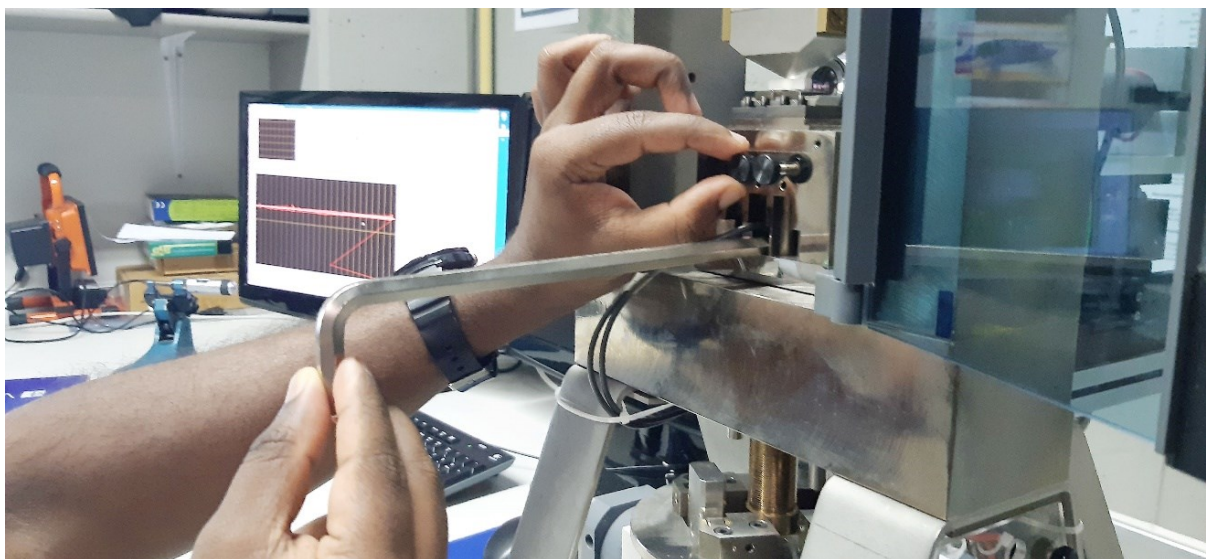


Figure 14: Procedure for adjusting the position encoders (displacement sensors).

Begin by inserting the wrench below the position encoder in such a way that the position encoder is in the lowest possible position. Use one hand to hold the wrench, with the other hand touching the corresponding black knurled screw, ready to fix the screw when the active range is reached. The related display for the position encoder on the left monitor shows the mechanical limit of $+58\ \mu\text{m}$ (Fig. 18). Now, move the position encoder upwards by very slowly lowering the wrench (see Fig. 14). At a certain point the display jumps from $+58\ \mu\text{m}$ to $-58\ \mu\text{m}$. However, this transition is not the one that we are looking for. Slowly continue moving the position encoder upwards until the active range is suddenly reached. If it is moved up too fast, the display jumps back from $-58\ \mu\text{m}$ to $+58\ \mu\text{m}$. In this case, the active range has been missed we must lower the position encoder and try again. When the active range has been found, hold the position stable between roughly $-50\ \mu\text{m}$ and $-10\ \mu\text{m}$ and immediately fix the position encoder with the black screw. It is not necessary to fix it at $0\ \mu\text{m}$. If the position is fixed at a positive value, it would also work, but the measurement range from there to the limit of $58\ \mu\text{m}$ would be small. Therefore, a negative starting value is preferred.

This must be done with both position encoders if both are to be used. When this is finished, it is sometimes helpful to use a metal piece and to tip with it slightly against the lower and upper support in order to remove settling effects between the sample and the support rollers. In this case, the specimen should be clamped with a few Newton (5 N, 10 N, or similar). Do not use the hexagonal wrench because it responds to the magnets and would disturb the positioning of the sample. Rather use, for example, template (5) in Fig. 13. If any settling happens, this can be seen in the force signal and in the (large) load-displacement diagram. The force decreases by a few Newton. And, in principle, that is it. If the pulse counter of the step motor is being used rather than the position encoders, the effective range is much larger (up to 20 mm, mechanically limited) and thus the procedure described here is not necessary.

4. General options and different kinds of tests

4.1 Some basic aspects

Important points concerning the use of the machine are summarized as follows:

1. Switch on the main electronics *before* switching on the computer. Ensure that the fans positioned at the upper surface of the electronic rack are working and cooling the interior of the rack. The password for starting the computer is "user."
2. If a LabView Instruments window pops up, *do not* start a LabView update! If LabView 2011 is updated to a newer version, the program *will no longer work!*
3. Ensure that the sound for the end switches is enabled. This means that the upper switch on the back side of the machine (Fig. 6) is in the lower position.
4. After starting the program and before clamping the sample, ensure that the green LED in the charge amplifier of the force sensor is on. If not, the clamping procedure will destroy the sample.

5. If the bending bar has been adjusted and the cross head is to be fixed, first tighten the two wing screws on the right with the special key (see (4) in Fig. 13) and then gently tighten the two black screws on the left.
6. Before starting the measurement, close the blue safety glass.
7. Do not move the lower support (by hand or motor) beyond the permitted range limited by the end switches!
8. When using the actuator, bear in mind that it works with a high voltage – up to 1 kV.
9. Do not kink or strain the thin cables on the back side of the machine that run out to the right of the base plate and enter the 19-inch cabinet (rack) under the table.
10. Generally, be careful with the microscopic optics of the CCD camera so that the lens does not touch any mechanical part of the machine.
11. When the pop-up window appears during program start, do not press any buttons outside this pop-up window – this may cause a program crash.
12. At the end of the measurement, terminate the program by using the correct “Stop” button for the program (at the bottom, right corner on the left monitor).

Rules when disassembling parts of the machine:

1. Take care when tightening screws after removing them from or fixing them to aluminum parts. Too much force (moment) would damage the aluminum threads.
2. The rubber bands at the camera mounting should be replaced from time to time because after some months they become brittle. These stabilize the microscopic image when the step motor is working.
3. Also the air pressure in the damping feet of the machine should be checked after some months. An appropriate air pump is available in the cabinet of the spare parts.
4. If necessary, the blue safety glass can be completely removed, because the two polymer grip bars are fixed to the main frame only by (strong) magnetic force.

4.2 4-point bending (R-curve)

Basic function of the program

Measurements in 4-point bending are only possible with support distances of 20 mm and 40 mm (see Fig. 7). The specimens should have a minimum length of 45 mm (42 mm). After

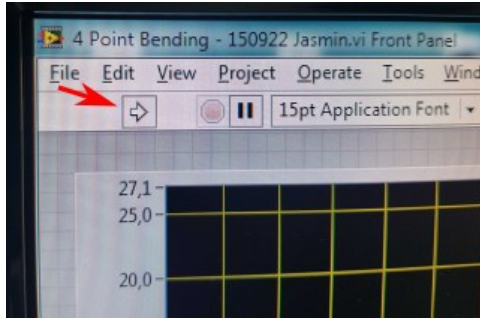


Figure 15: Arrow button to start the program.

double clicking on the current program file, “4 Point bending – 151215 Jannik” or “4 Point Bending – 150922 Jasmin,” the LabView program is started by clicking the small arrow in the upper left corner of the (left) control screen (see Fig. 15). When the pop-up window appears, type in all of the data (height, width, notch depth, etc.) concerning the specimen being used and adjust the lower left and right switches (Fig. 16). The switch at “Pos. Encoder” must be in the position “ON” if

the position encoders with a maximum range of 116 μm ($\pm 58 \mu\text{m}$) are to be used. If more displacement is expected, e.g., with polymer samples, the switch should be at “OFF.”

If the compliance method is to be used to determine the crack length, the right switch must be at “4-Point” and “Pos. Encoder” must be ON. The predefined file names contain the date and time of day so that the files are saved in a chronological order. However, a signature describing the measurement should be appended to the file name. This makes it much easier later on to find the corresponding files. The start window is then closed by pressing the “OK” button.

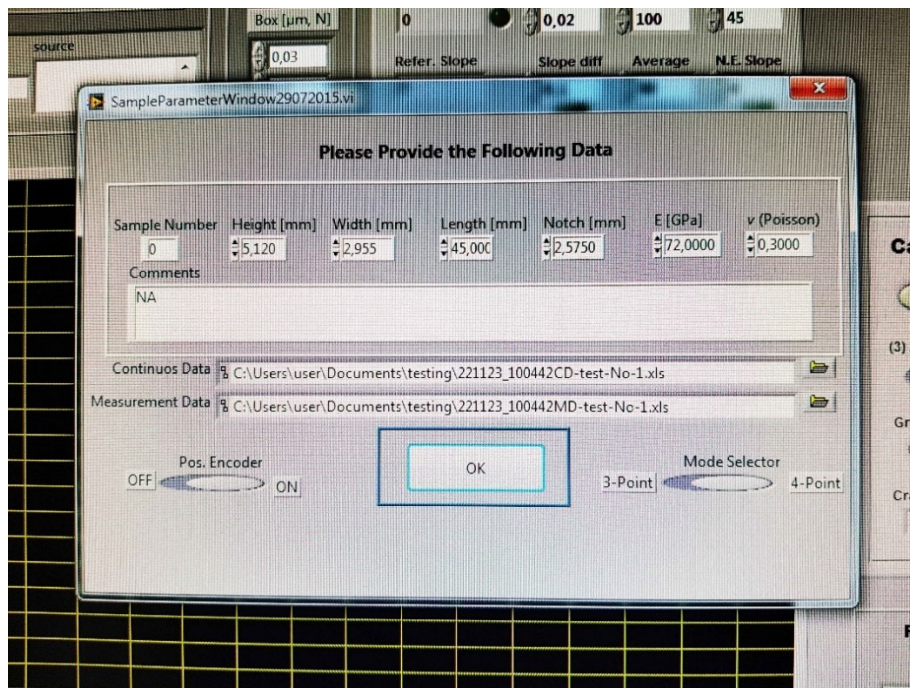


Figure 16: Pop-up window at program start. The file with “MD” in its name (measured data) contains only the white points in the load-displacement diagram (Fig. 20) and the file with “CD” in its name (continuous data) contains all of both the red points and the white points. A white point can be created at any time by pressing the middle wheel button of the computer mouse. Note that the correct Young’s modulus must be inserted “E [GPa]” if the compliance method (crack length) is used.

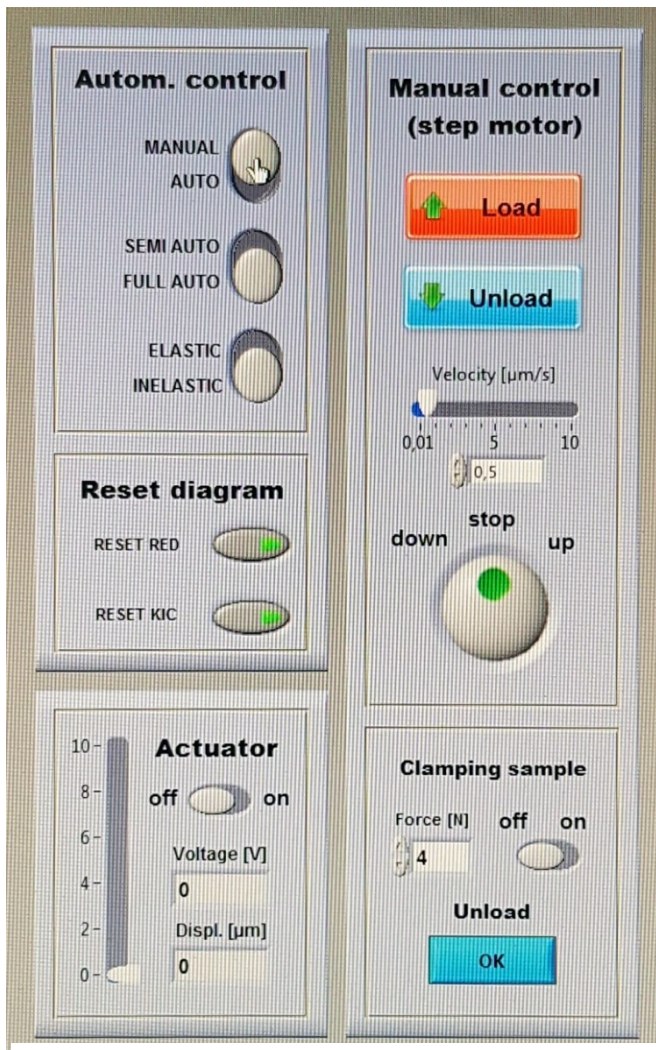


Figure 17: Control panel for operating the machine.

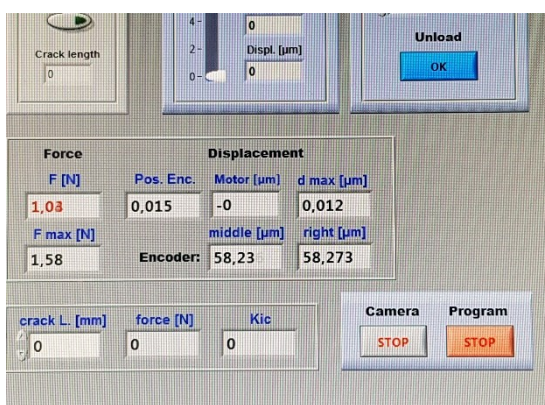


Figure 18: Force and displacement display area.

When the bending bar is placed in the load cell, the cross head should be lowered by turning the control wheel of the adjustment screw (Fig. 4) until the upper rollers touch the sample. Then, carefully continue lowering the cross head until there is only a small gap left (ca. 0.3 mm) at the contact point (see Fig. 7). Care needs to be taken – if full contact is obtained at this point, the full weight of the cross head will be on the sample and the sample is likely to break.

When this has been done, fix the cross head (wing screws), reset the force by pressing the green button in the charge amplifier twice, and ensure the green LED is on! The sample can then be automatically clamped by switching the button in the field “Clamping sample” to “on” (Fig. 17). The clamping force can be adjusted in the same field.

After this, the position encoders must be placed in such a way that they touch the specimen and that they will operate in their active displacement range. Their active range is between $-58 \mu\text{m}$ and $58 \mu\text{m}$. Slowly push up the position encoders while observing the corresponding number at “Encoder” (“middle [μm]” or “right [μm]” in Fig. 18).

Note: The field “right [μm]” is also valid for the position encoder mounted in the left position. Try to adjust the position encoders to a negative number, e.g., $-50 \mu\text{m}$ or $-10 \mu\text{m}$, because then the available displacement range up to $+58 \mu\text{m}$ is larger.

When everything has been mechanically adjusted, switch to “FULL AUTO” and “INELASTIC.” “INELASTIC” refers to materials that are not perfectly linearly elastic, like glass. Normally, the reference slope at which the machine partially unloads must be repeatedly adjusted during the measurement. The “ELASTIC” option does this adjustment automatically, but thus far it only works for glass. In this case, the “Slope diff” display is active, and the slope difference

between the last unloading slope and the reference slope is kept constant. However, if the material shows a slight hysteresis during the partial unloading, the “ELASTIC” option does not work.

More parameters and options

Figure 19 shows the main parameters that define and control the measurement. The individual parameters are explained in the list below.

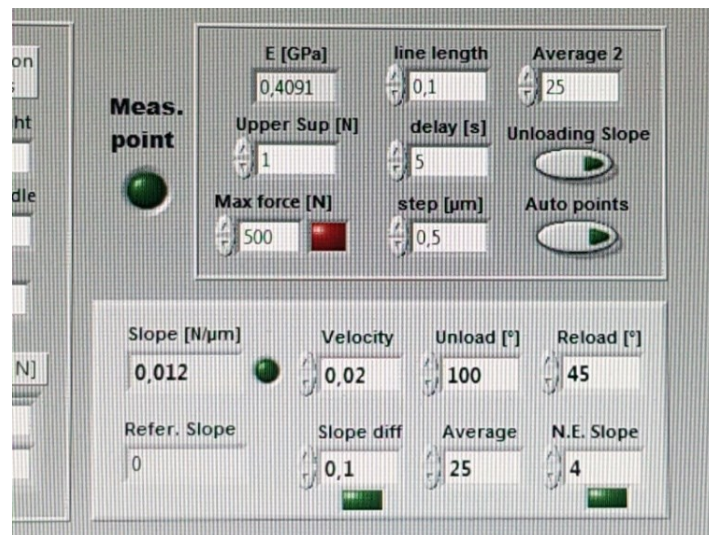


Figure 19: Different control parameters (mainly to obtain stable crack advance).

- “E [GPa]”: If bending is performed with a specimen without a notch using the 20/40mm load cell and two position encoders, Young’s modulus is given here, calculated from the slope in the load-displacement diagram. This value is necessary if the compliance method for the crack length determination is applied.
- “Line length” defines the visual length of the line, showing the slope in the load-displacement diagram. The slope is calculated by linear regression.
- “Average 2” denotes the number of data points used for the linear regression mentioned previously (25 is the current value).
- “Upper Sup [N]” (upper support): Here, the dead weight can be defined.
- “Delay [s]” is the delay time after partial unloading before the automatic mode is activated again. This time period enables stabilization of the slope.
- “Unloading slope”: Function not clear (has probably to do with the ELASTIC option).
- “Max force [N]” is the maximum force that can be reached. At this point, the motor will stop. The charge amplifier (with the green LED) can measure forces up to ca. 800 N, because then the maximum charge in the charge amplifier is reached.
- “Step [μm]” denotes the average step width of the “auto points.”
- “Slope [N/μm]” is the current slope in the load-displacement diagram.
- “Velocity” denotes the loading speed referring to the displacement, measured in μm/s. (A usual value for R-curve measurements and ceramic materials is 0.02 μm/s.)
- “Unload [°]” is the amount of partial unloading given in degrees [°] of the rotation of the handwheel and step motor axis, respectively. A full turn (360°) corresponds to an approximately 12.2 μm change in the displacement (1 mm/82 = 12.195... μm).

- “Reload [°]” is the rapid reload immediately after unloading. It overcomes the “screw slackness” of the moveable mechanics, including the gear unit.
- “Refer. slope” is the current slope difference for unloading belonging to the “ELASTIC” option.
- “Slope diff” denotes the “reference slope difference”, calculated by the program, if the option “ELASTIC” (Fig. 17) is being used.
- “Average” shows the number of points used for the calculation of the slope by linear regression. The difference between “Average” and “Average 2” is not clear. In order to be on the safe side, these should be identical (usual value is 25).
- “N.E. slope” (non-elastic slope = inelastic slope) indicates the reference slope for when the sample should be unloaded. When the current slope “Slope [N/μm]” reaches the “N.E. Slope” value, the unloading procedure will immediately start. This is the parameter that must be repeatedly adjusted during the measurement of an R-curve.

Additional features are shown in the overview of the control panel (Fig. 20). In the upper left corner, a preliminary R-curve (1) is shown. Due to the electronic drift of the force signal, the R-curve has a decreasing plateau instead of a horizontal one. This drift can also be seen in the load-displacement diagram below (2), where the data points for complete unloading decrease continuously. A polynomial must subsequently be fitted to these points and subtracted from the force data, which will move these unloading points to a constant level. The dead weight on the sample given by the upper support (and slight force of position encoders), which is additional load on the sample, must be taken into account after the test.

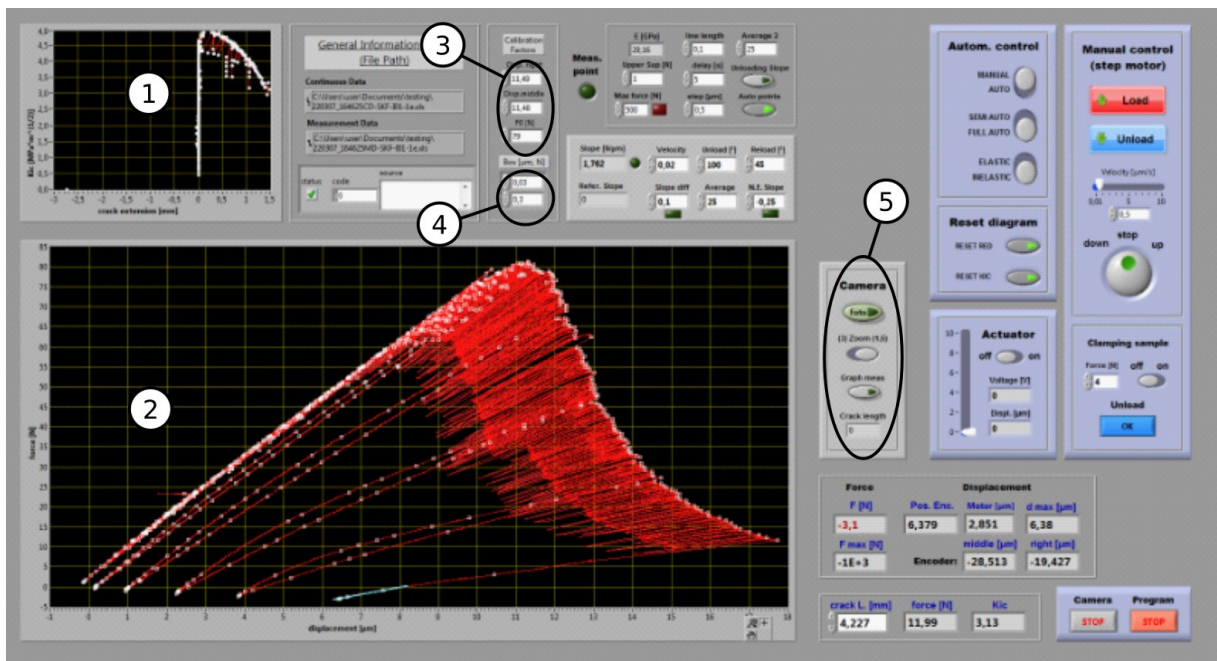


Figure 20: Control panel after measuring an R-curve: (1): preliminary R-curve without drift correction; (2): load-displacement diagram; (3): parameters for the calibration of displacement and force; (4): dimensions of the “box,” which defines the minimum distance between the data points and prevents that data are recorded continuously when the force is constant for a period of time. (5): control for camera. The “foto” button allows the current microscopic image to be saved.

If the charge amplifier has been reset, the predefined value is +1.2 N. This value takes into account the weight of upper stainless steel support (see (2) in Fig. 12) and the low forces of

the position encoders reducing the dead weight correction. If the hard metal support (see (1) in Fig. 12) is used, the dead weight correction is +3.1 N, meaning that, ultimately (after the correction), the total unloading procedures should all end at 3.1 N. In the case of 3-point bending, there is no dead weight and the cycles of total unloading should end at zero N. The corresponding correction must be made after the measurement. The three parameters (3) allow for the calibration of displacement and force (see sections 5.6 and 5.7). The two parameters in (4) determine the size of the “box”, which defines the minimum distance between the data points. In the control panel (5) of the camera, only the “foto” button is active. Pressing this button stores the current video image. (Note: Do not press this button when any pop-up windows are open! This also applies to any other buttons outside a pop-up window.)

During the measurement

When initially loading the sample or during complete unloading, activating “Auto points” is recommended. The initial load increase can be performed manually by pressing the red “Load” button. After reaching a medium force and before the crack growth is expected to start, the “MANUAL/AUTO” button should be switched to “AUTO.” The two buttons below this should be on “FULL AUTO” and “INELASTIC.” The value at “N.E. Slope” (Fig. 19, N.E. = non-elastic) must be *slightly* lower than the actual slope at the position “Slope [N/μm].” Even if no crack advance can be seen on the video image, the machine can partially unload because the crack will start in the middle of the notch front inside the specimen.

When the loading curve starts to bend to a lower slope or when the crack can be seen with the microscope, the button “Auto points” can be switched off. During the test, as the crack becomes longer, the reference slope (at “N.E. Slope”) must be continuously adjusted to lower values and always be kept slightly smaller than the current slope. For control purposes, every five or ten data points an “optical” point can be recorded by switching to SEMI AUTO and determine the crack length optically. Every 20 to 30 minutes the sample should be totally unloaded to obtain the current “zero force.” An image of the video picture can be stored at any time by pressing “foto” during the automatic run (if no pop-up window is open).

Finally, when the measurement is finished, the specimen should be completely unloaded and two or three measuring points taken in order to obtain a final data point for the drift correction. The measurement should be stopped using the following procedure:

1. Recommended: Take a screenshot and store it in an Impress or PowerPoint file. Screenshots of subsequent tests can be stored in the same file.
2. Press the “Program STOP” button so that the data files are properly closed.
3. The data files and stored video pictures can be found in the “Dokumente/testing” folder. Create a folder with your name and copy the files into your folder.
4. If another test is planned, adjust the new specimen and restart the program by pressing the arrow button (Fig. 15). If no other test is intended, close the LabView windows.
5. If a National Instruments window pops up, close the window without starting any update. This will take some time.
6. Copy your data onto a USB stick and shut down computer and electronics.
7. Place all templates, keys, etc. where they belong and leave the whole working place clean, taking all your samples with you.

4.3 3-point bending (R-curve)

Figures 21–23 represent several parts of load cells for 3-point bending with different load geometries. The part labelled (4) in Fig. 21 is the upper support for a compression test.

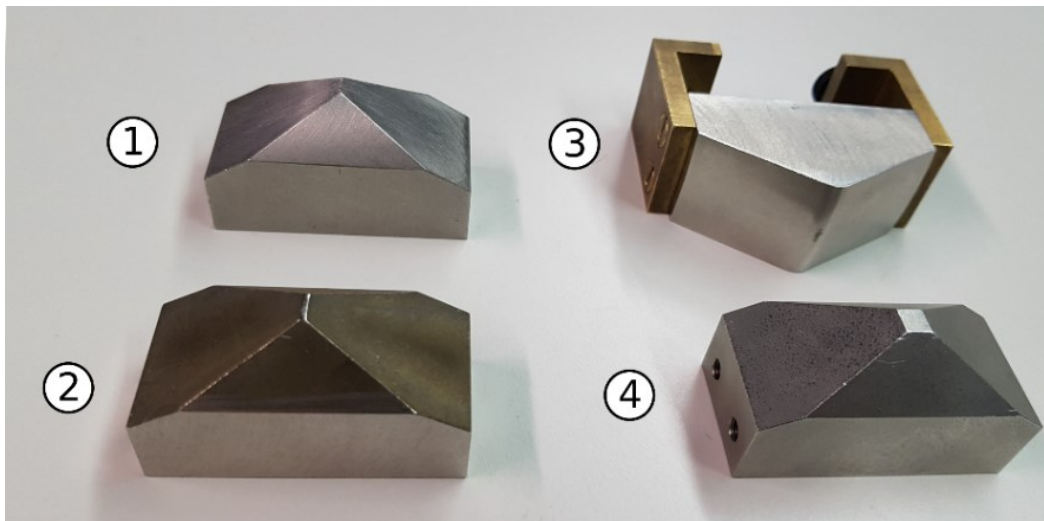


Figure 21: Different upper 3-point bending supports: (1): upper support with relatively sharp tip; (2): tip radius ca. 0.5 mm; (3): tip radius 2.5 mm; (4): upper support for compression test, area 5 x 5 mm². If a tip other than (3) is used, the L-shaped brackets must be dismantled and mounted to the new tip.

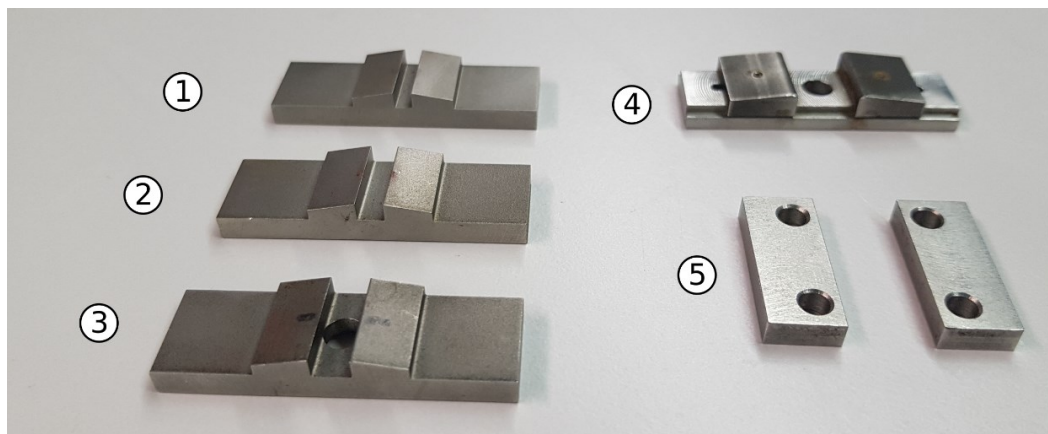


Figure 22: Different lower supports for 3-point bending: (1): support distance 3 mm; (2): support distance 4 mm; (3): support distance 5 mm; (4): support distance variable from 7 mm to 25 mm; (5): distance spacer to reduce the lower support distance from 40 mm to 20 mm.

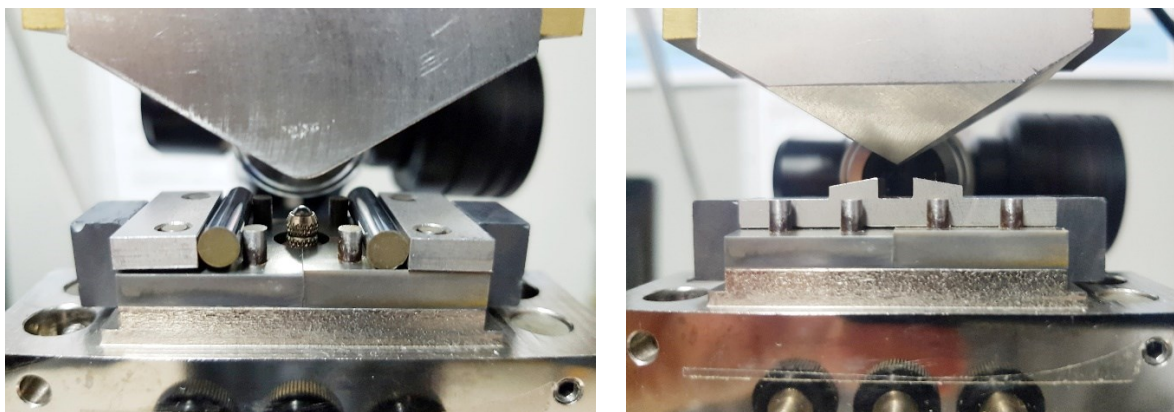


Figure 23: Two different 3-point bending load cells. **Left:** support distance 20 mm using spacers (see (5) in Fig. 22). **Right:** support distance 5 mm (see (1) in Fig. 21 and (3) in Fig. 22).

When starting the test, the button “Mode Selector” in the initial pop-up window (Fig. 16) must be switched to “3-Point,” and the button “Pos. Encoder” must be placed accordingly at either ON or OFF. ON means that the middle position encoder will be used with an active range from $-58\ \mu\text{m}$ to $58\ \mu\text{m}$. Thus, if the displacement will exceed 100 or $110\ \mu\text{m}$, the option OFF must be selected, meaning that the pulse counter of the step motor is applied to determine the displacement. For relatively soft materials compared to ceramics, the option OFF is appropriate.

In principle, R-curve measurements are possible in 3-point bending, but the compliance method for determining the crack length cannot be used. The compliance method only works for 4-point bending with support distances of 20 and 40 mm, because in this case the difference between two position encoders is applied to calculate the pure bending compliance of the specimen without additional machine compliance. Thus, in 3-point bending, the crack extension can be measured only optically with the microscopic video image.

The optical measurement is normally done with the magnification corresponding to the left scale (Fig. 24). The scale, left or right, can be chosen by adjusting the zoom optics to factor 1.5 or 3, respectively. The scale at the zoom optics has discrete positions so that the factors can be chosen easily. In Fig. 24, the crack tip can be seen but not the notch tip. Therefore, the distance from the horizontal $0\ \mu\text{m}$ axis to the notch tip must be added to the current position of the crack tip at ca. $0.195\ \text{mm}$. For optical measurement, the second button on the left in Fig. 17 must be switched to “SEMI AUTO.”

If the machine partially unloads during the measurement to stop the advancing crack, a pop-up window appears and the crack extension measured from the notch (!) tip, must be inserted. Note that this crack extension must be given in mm!

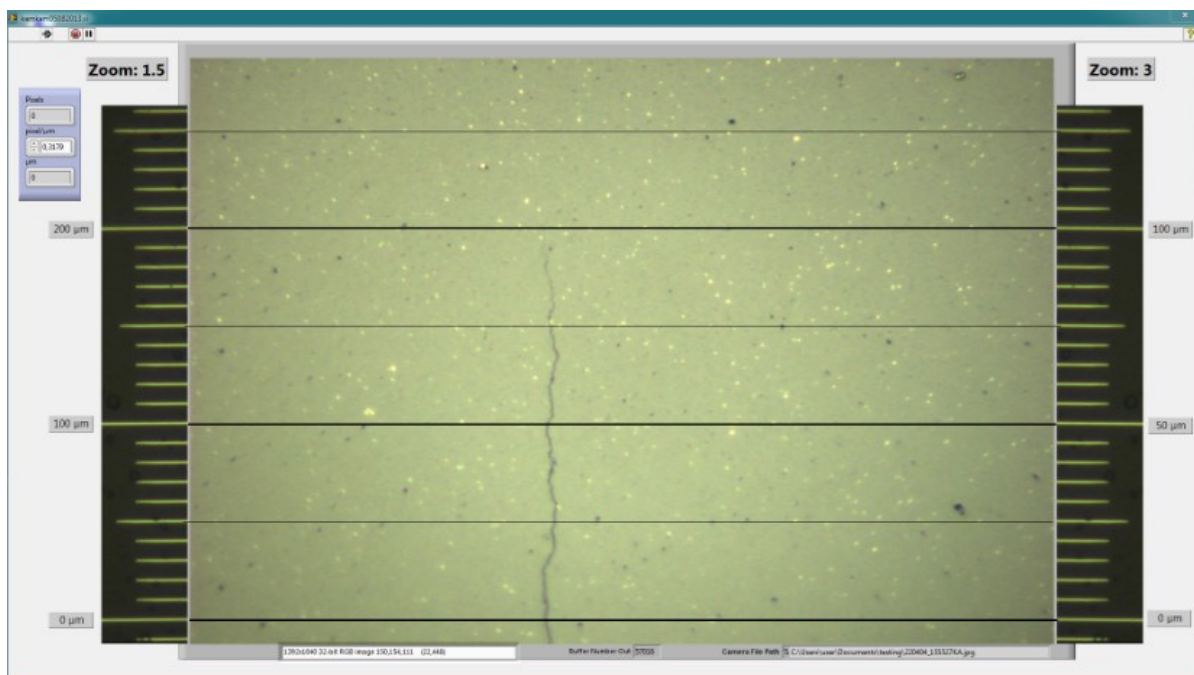


Figure 24: Screenshot of the right monitor with the video image of the crack. In this case, the left scale is valid.

4.4 Unstable fracture (K_{IC})

If the K_{IC} is to be determined by unstable fracture, e.g., with SEVNB, the sample must have a sharpened notch with a defined depth. After adjusting the sample and setting up the program, the measurement can be started using the big round button with the green dot (Fig. 17) by turning it to UP. The step motor starts and the sample is loaded until it fractures. Note that the step motor does not stop automatically; it must be stopped manually by turning the round button back to the “stop” position or by briefly pressing the red “Load” button or the blue “Unload” button.

In such measurements, the “Velocity” value (Fig. 19) is normally set to a higher speed, such as 1, 5, or 10 $\mu\text{m/s}$. If the loading speed is very low, subcritical crack growth can influence the results, meaning that the measured fracture toughness is decreased.

4.5 Strength measurement

The measurement of the bending strength is performed in almost the same way as the K_{IC} -tests with unstable fracture. The only change is that the specimen is without a notch. To obtain reasonable strength values of the material, the side of tensile stress, which is the bottom surface of the specimen, should be polished.

Note that the maximum electric charge for the charge amplifier corresponds to a maximum force of ca. 800 N. Normally, the force is limited to 500 N (see “Max force [N]” in Fig. 19). The given value should not be higher than 800 N. If higher forces are expected, the ATS testing machine in the furnace room (on the ground floor in the building of our institute) must be used. Thus, if an unstable fracture is planned using the BM2 machine, the specimen should be relatively thin, e.g., with a cross section of 2 x 3 mm^2 or less, depending on the material.

4.6 Compression test

Compression tests for measuring the compressive strength or the limit of elastic deformation in a load-displacement diagram can be done with the setup in Fig. 25 – see also (6) and (7) in Fig. 12. Here, the measurement must also be stopped manually.

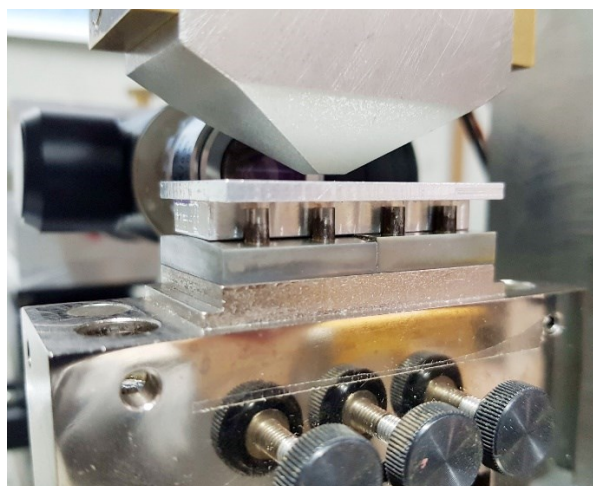


Figure 25: Load cell for a compression test (no sample).

Note that the sample should be very small with a horizontal cross section of between $1 \times 1 \text{ mm}^2$ and $2 \times 2 \text{ mm}^2$, because otherwise the necessary forces would be too high.

4.7 Measurement of Young's modulus E

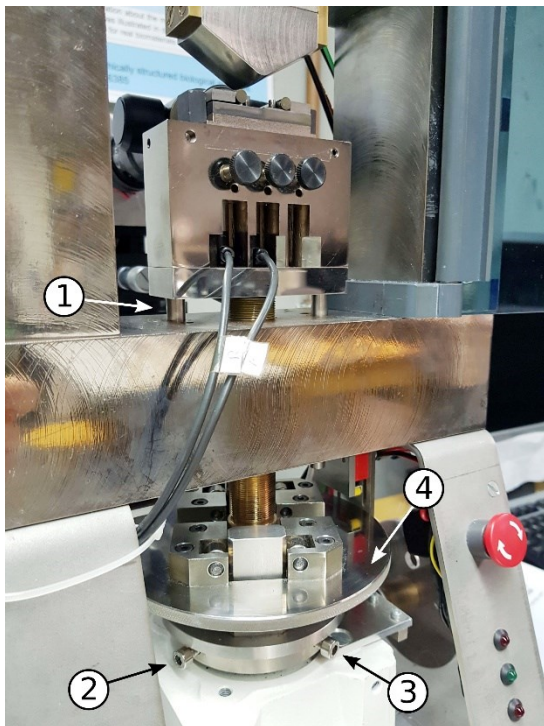
Young's modulus can be precisely measured using the load cell with 20 mm and 40 mm support distances. A sample of approx. 45 mm length without a notch must be used. The sample is loaded and unloaded elastically. The current Young's modulus is then provided in the field "E [GPa]" (see Fig. 19). It can also be calculated by means of the slope in the load-displacement diagram (recorded data) and by using Eq. (7) in Appendix A.

4.8 Fatigue test

Fatigue measurements are currently not possible with the machine BM2. In principle, the red ferroelectric actuator above the force sensor can be operated with a modulated voltage (sine function). However, this has not been necessary until now and thus is not included in the LabView program. If necessary, a mechatronics student should be able to modify the program accordingly.

5. Problem-solving

5.1 Mechanical reset of lower support



After performing several measurements, the lower support might have moved upward so that a larger gap is visible between the lower support and the frame (see (1) in Fig. 26). Moving the lower support down again using the step motor or the hand wheel would be very time consuming. This can be achieved in a much quicker way if the two screws at (2) and (3) are opened (one turn is enough). The round plate (4) can then be turned and the lower support can be moved downward until a tiny gap between support and frame at (1) is left. Finally, the two screws at (2) and (3) are fastened again.

Figure 26: The plate (4) can be turned quickly in order to reduce the gap at (1) when the screws (2) and (3) are opened.

5.2 Sample breaks during clamping procedure

If the sample breaks during the automatic clamping procedure, this could have different reasons:

1. When automatically clamping the sample with the corresponding button, the green LED at the charge amplifier was off and the force measurement thus did not work.
2. The force signal at the charge amplifier was not reset. The “zero force” could have been, e.g., -8 N, and when the machine stopped at the reference force of 4 N, the sample was already loaded with 12 N, which could have been too much.
3. The reference force, which should normally be 3 N or 4 N, was too high for the specimen.

5.3 LabView program crashes or stops responding

If the LabView program stops responding and the screen is frozen, try the following:

1. Close the LabView program by clicking on the cross in the upper right corner. If this does not work:
2. Close the program with the Task Manager. Then close the “National Instruments” window and restart the LabView program. Never update or upgrade LabView!
3. If this still does not work, shut down the computer. If this also does not work, press the on/off button of the computer for more than 5 seconds until the computer is off. Shut off the electronics.
4. After 10 or 20 seconds, switch the electronics on and restart the computer. Start the LabView program.
5. If none of the above work, call Manfred!

5.4 No displacement signal

If one or both displacement sensors (encoders) are not giving a signal on the main panel, check the electric fuses behind the back door of the rack. To do this, switch the main power off and switch the step motor on (with main power off). This ensures that the capacitors in the electronics are completely discharged. The positions of the fuses are indicated in Fig. 11. If one or more fuses have to be replaced, use a new one with the same strength and characteristics of the old one. If this does not solve the problem, check the cables of the position encoders for loose connections. In this case, the defect position sensors will need to be repaired or replaced by new ones of the same type.

5.5 Procedure for removing the lower support

In cases where the lower support needs to be removed, e.g., to access the position encoders, this is possible without needing to open the solid main frame. The procedure is described step by step as follows:

1. Move the lower support completely downward using the step motor or hand wheel so that it has full contact with the main frame. There should be no gap.
2. Remove the movable upper part of the 3-point or 4-point load cell.
3. Slightly open the grub screws (Madenschrauben) at positions (1) and (2) in Fig. 27. The two long guiding rods will probably fall down, but they cannot be removed in this way. Move both of these up and slightly shift the lower support horizontally so that the rods rest on the main frame and do not fall down again (see Fig. 27). Now tilt the whole part and remove both guiding rods.

Caution: The guiding jackets in the main frame have precisely the diameter of the guiding rods so that the latter can move easily without any backlash or clearance. Handle the guiding rods with extreme care and do not use any force since this can damage the guiding system. All parts can be taken out easily without force!

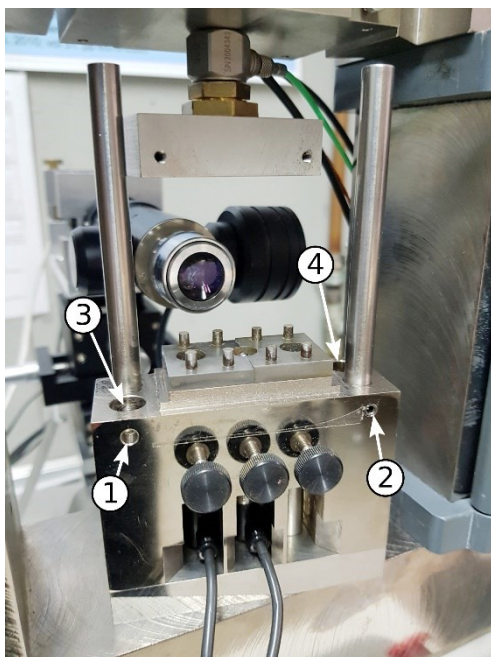


Figure 27: The two long guiding rods are moved upward in order to remove the entire lower support of the load cell.

4. Open the screws that hold the ground plate in holes (3) and (4). For this, it is necessary to move again or completely remove the grub screw at position (1), since otherwise the screw at position (3) cannot be accessed. By holding the lower support in your hand, open the screws at (3) and (4) completely and then remove the ground plate.

5. The position encoders (sensors) can now be removed. In this case, be careful not to lose the clamping jaws (see (2) in Fig. 28 and (3) in Fig. 29). The cylinder (3) in Fig. 28 is only a place holder because no position sensor is mounted here. It also ensures that the corresponding clamping jaw is not lost. **Caution:** Do not mount the position sensors without the clamping jaw, because otherwise the fixing screw will damage the position sensor.

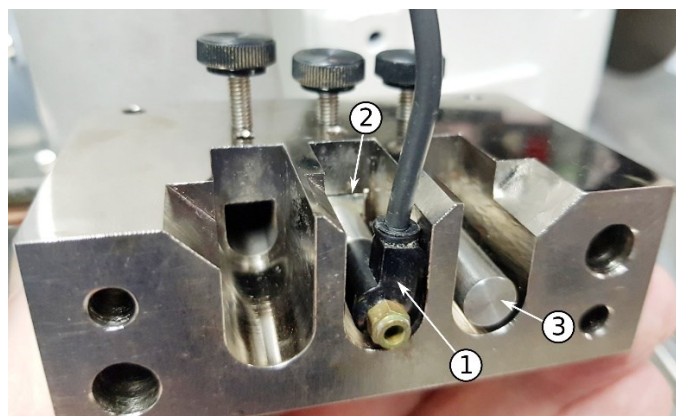


Figure 28: Lower part of the load cell with (1): mounted position sensor; (2): mounted clamping jaw; (3): dummy cylinder (which mainly ensures the corresponding clamping jaw is not lost).

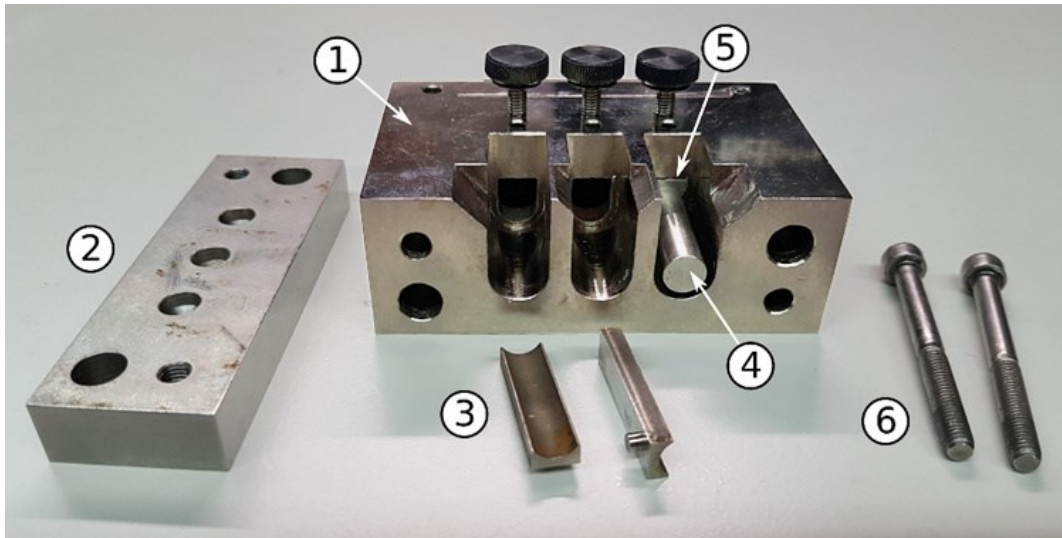


Figure 29: The lower support is disassembled including the following parts: (1): Main part of lower support; (2): ground plate; (3): two clamping jaws; (4): dummy cylinder replacing one sensor; (5): mounted clamping jaw; (6): screws to fix the ground plate. (The position sensors are not shown.)

Figure 29 illustrates the separated parts (without position encoders). When the lower support needs to be mounted again in the main frame, perform the above steps in the reverse sequence. Ensure that the polished side of the ground plate is at the front side of the machine.

Caution: When the clamping jaws, the sensors, and the ground plate are mounted, do not completely fix the screws (6) in Fig. 29, but leave them slightly loose before the guiding rods are mounted. First insert the guiding rods before fixing them. Check whether the whole lower support can easily move up and down and then fix the screws (6) that hold the ground plate at positions (3) and (4) in Fig. 27.

5.6 Checking the calibration of the displacement sensors

The central screw (see Fig. 4) that moves the lower support has a pitch of exactly 1 mm, implying that one full turn moves the lower support by 1 mm. The gear unit has a reduction of 82:1. This means that 82 turns of the hand wheel or the step motor cause a displacement change of 1 mm. Thus, one turn of the hand wheel or the step motor means a change in the displacement of $1000 \mu\text{m}/82 = 12.195 \mu\text{m} \approx 12.2 \mu\text{m}$, and five turns accordingly mean $5000 \mu\text{m}/82 = 60.9756 \mu\text{m} \approx 61 \mu\text{m}$. The calibration of the displacement sensors can be performed as follows:

1. Disassemble the removable part of the upper support and move the cross head downwards as far as possible (down to the “stop screws”).
2. Fix the wing screws! Then move the lower part of the load cell upward until there is a gap of only a few millimeters.
3. Start the LabView program. Then move the position sensors up until they are in contact with the upper metal plate (see Fig. 30) and adjust them within their measuring range so that they show a negative displacement, e.g., between $-50 \mu\text{m}$ and $-10 \mu\text{m}$.

4. Now, turn the handwheel exactly five times and note the change in displacement on the control panel. It should be $61\ \mu\text{m}$. (Take into account that the handwheel/gear unit has a screw slackness that has to be removed before rotating.)
5. If the displacement change is not $61\ \mu\text{m}$, adjust the corresponding calibration factor(s) (position (3) in Fig. 20) accordingly and check the displacement change again.
6. This can also be done with one full turn of the handwheel, which should result in a movement of $12.2\ \mu\text{m}$.

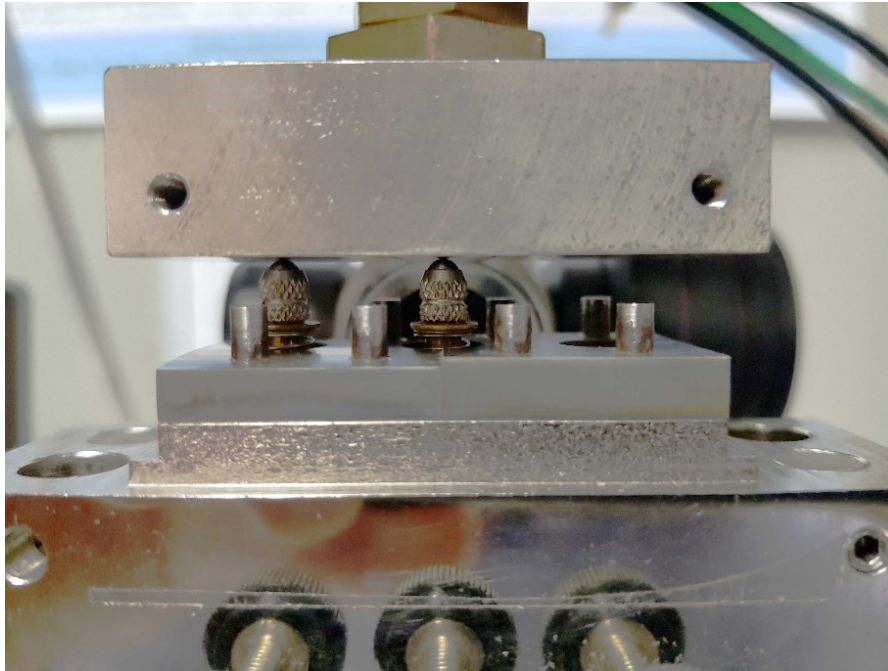


Figure 30: Arrangement of upper and lower support as well as the position sensors in order to adjust the displacement calibration.

5.7 Checking the force calibration

The force can be calibrated with a steel block of a weight (force) of $50.19\ \text{N}$ (located, as you enter the AFM room, to the right on the table close to the wall). In this case, follow the steps below:

1. Place a strong sample or a plate of any kind into the load cell and lower the upper support until there is full contact with the sample or plate. The load of the mechanical part on the sample (cross head, red actuator, etc.) will now be more than $40\ \text{N}$ (i.e., the sample should be strong). If the full weight is on the sample, the upper large horizontal hand wheel for moving the upper support can be freely rotated.
2. Reset the force by pressing the green button at the charge amplifier twice, which will result in a force value of $1.2\ \text{N}$.
3. Then carefully place the weight of $50.19\ \text{N}$ on top of the machine, as in Fig. 31. The force value on the control panel should increase by $50.19\ \text{N}$.
4. If this is not the case, adjust the calibration factor of the force (position (3) in Fig. 20) accordingly and check again.



Figure 31: Mechanical arrangement for the force calibration.

5.8 A wing screw is broken

There has already been an instance where a wing screw broke just at the surface of the cross head. If this happens, the part of the screw in the thread cannot be gripped with engineers' pliers from the front, and access from the back side is also not possible. When this happens, do not drill (!) or similarly try to remove the remaining part of the screw! Follow these steps:

1. Completely remove the lower part of the load cell as described in section 5.5.
2. Remove the upper movable part of the load cell.
3. Remove the thin green cable from the force sensor.
Caution: Do not touch the pin of the plug of the green cable and the pin of the plug at the sensor. If possible, cover the plugs with the corresponding protection caps.
4. Carefully remove the metal plate at the charge sensor and then remove the sensor itself. Do not remove the large actuator.
5. Loosen the brass screw below the upper hand wheel and completely remove the upper central screw that allows the upper support to be moved. When doing this, hold the upper hand wheel in position until the upper central screw is removed.
6. Remove the upper horizontal part of the main frame by taking out the six large screws on top of the frame so that the frame is open at the top. The space below the actuator within the main frame should be completely free.
7. Use an ordinary car jack (lifting jack) and place this car jack in the empty space within the main frame to push the actuator and the cross head up with force (but carefully), until it pushes out of the U-shaped open frame.
8. Grip the broken screw from the back side with appropriate pliers and remove it from the cross head.
9. Reassemble the mechanical parts and replace the broken screw with a new one.

6. Note to BM2 instruction (Einweisung)

When instructing another person (student) concerning the operation of BM2, allow that person to do everything by themselves, i.e., the supervisor should not both explain and at the same time press and adjust buttons (in this way, the student will learn almost nothing). The supervisor can demonstrate it once, but after this the student should perform any actions by themselves with their own hands! From the beginning, I get the student to take a seat on the operator chair in front of the keyboard, open the rack with the key, switch on the electronics, and start the computer and program, etc. This way has always been successful. Before a new person performs an R-curve measurement alone, the supervisor should accompany and assist the person during one or two measurements, which normally takes a few hours. For the first tests, it is of course better to use specimens that are not very valuable.

Acknowledgments

Many thanks goes to Dipl. Ing. Anja Borchert for providing a smartphone for accurate photos of the bending machine.

Appendix A (Main equations)

4-point bending

The main equation used for the calculation of the fracture toughness in the so-called R-curves is taken from Munz und Fett [4]. Here, K_I is the stress intensity factor and fracture occurs at $K_I \geq K_{IC}$, with K_{IC} being the critical stress intensity factor or fracture toughness.

$$K_I = \frac{3F \Delta s}{2bh^2} \sqrt{a} \Gamma_M(\alpha) \quad (1)$$

with

$$\Gamma_M(\alpha) = \frac{1.1215\sqrt{\pi}}{(1-\alpha)^{3/2}} \left[\frac{5}{8} - \frac{5}{12}\alpha + \frac{1}{8}\alpha^2 + 5\alpha^2(1-\alpha)^6 + \frac{3}{8} \exp\left(-6.1342 \frac{\alpha}{(1-\alpha)}\right) \right] \quad (2)$$

The maximum force is F , $\Delta s = s_2 - s_1$ is the difference between the support distances of $s_2 = 40$ mm and $s_1 = 20$ mm (used in the LabView program), a is the crack length, h and b the height and the width of the sample, $\alpha = a/h$ the relative crack length, and $\Gamma_M(\alpha)$ the geometric factor. These equations can be used for stable and unstable fractures and have the advantage that the geometric factor is valid for the whole range from $\alpha = 0$ to $\alpha = 1$.

3-point bending

The equation for 3-point bending is taken from Fett and Munz [5]:

$$K_I = \frac{3FL}{bh^2} \sqrt{a} \Gamma_M(\alpha) \quad (3)$$

The geometric factor is:

$$\Gamma_M(\alpha) = \frac{\sqrt{\pi}}{(1-\alpha)^{3/2}} \left[0.3738 \alpha + (1-\alpha) \sum_{\mu, \nu=0}^4 A_{\mu\nu} \alpha^\mu (h/2L)^\nu \right] \quad (4)$$

In Eq. (3), L is half of the support distance and the other quantities are identical to those in Eqs. (1) and (2). Note that Eqs. (3) and (4), which can also be used for stable and unstable fractures, are not implemented in the LabView program. However, a subsequent data evaluation (after the measurement) must be performed anyway because of the necessary drift correction. The coefficients $A_{\mu\nu}$ are listed in the following table [5]:

Table A1: Coefficients $A_{\mu\nu}$ of Equation (4).

	$A_{\mu 0}$	$A_{\mu 1}$	$A_{\mu 2}$	$A_{\mu 3}$	$A_{\mu 4}$
$\mu = 0$	1.1200	-0.2387	0.4317	-1.7351	2.4145
$\mu = 1$	-1.8288	-0.2573	-4.9847	16.9047	-18.2883
$\mu = 2$	2.9741	0.2706	18.6767	-60.4912	59.9239
$\mu = 3$	-2.4280	0.5627	-27.3447	87.7078	-85.2405
$\mu = 4$	0.6712	-0.5184	13.5837	-43.5421	42.3503

Compliance method

The crack length is measured with the compliance method, where the compliance is given by $C = \partial\Delta/\partial F$, with Δ and F being the displacement and the force, respectively. (The compliance is the inverse stiffness.) Thus, the compliance is the inverse slope in the load-displacement diagram and is determined during each partial unloading of the sample. The crack length $a = \alpha \cdot h$ can then numerically be calculated using the following formulas:

$$C(\alpha) = \frac{9(s_2 - s_1)^2}{2Eb h^2} \int_0^\alpha \frac{\alpha' (Y(\alpha'))^2}{(1-\alpha')^3} d\alpha' + C_0 \quad (5)$$

with

$$C_0 = \left(\frac{s_2 - s_1}{h} \right)^2 \frac{1}{Eb} \left(\frac{s_2 + 2s_1}{4h} + \frac{(1+\nu)h}{2(s_2 + s_1)} \right) \quad (6)$$

The quantity C_0 is the compliance of the specimen without a notch [6], E is Young's modulus, ν the Poisson ratio, and $Y(\alpha) = \Gamma_M(\alpha) \cdot (1-\alpha)^{3/2}$. The Young's modulus was determined with

$$E = \frac{6625 \text{ mm}^3}{bh^3} \cdot s \quad (7)$$

[2], with s being the slope in the load-displacement diagram. The number 6625 has to do with the geometric arrangement of the load cell and the position encoders ($s_1 = 20$ mm, $s_2 = 40$ mm, distance between middle and left position encoder = 15 mm).

Appendix B (Summary of different load cell dimensions of BM1, BM2)

Table B1: Support distances and possible arrangements of supports of the two testing machines BM1 and BM2.

Bending machine	Load cell	Support distances [mm]	Mounting of support	Displacement meas. (number of sensors)	Special features
BM1	3PB	7	fixed	1	–
”	”	9	fixed	1	–
”	”	20	movable	1	also asym.
”	4PB	4 / 7	fixed	1	–
”	”	7 / 7	fixed	1	correction-m.
”	”	4 / 9	fixed	1	–
”	”	7 / 9	fixed	1	–
”	”	9 / 9	fixed	1	correction-m.
”	”	10 / 20	movable	1	also asym.
”	”	20 / 20	movable	1	corr./ asym.
”	compression	area $\approx 5 \times 5$	(movable)	1	–
BM2	3PB	3	fixed	step motor	also asym.
”	”	4	fixed	step motor	also asym.
”	”	5	fixed	1 / step motor	also asym.
”	”	7 – 25	fixed	1 / step motor	variable
”	”	20	movable	1 step motor	–
”	”	40	movable	1 / 2 / step motor	diff. displacem.
”	4PB	20 / 20	movable	1 / step motor	(not used)
”	”	20 / 40	movable	1 / 2 / step motor	diff. displacem.
”	compression	area 5×5	fixed	step motor	–

The table above shows the alternative load cell geometries for bending tests in the two testing machines BM1 und BM2. The abbreviations 3PB, 4PB, and “compression” refer to 3- and 4-point bending and compression test. Equal load distances, e.g., 20/20, are used in order to correct the results with respect to the machine compliance (“diff.” means differential). The rows, highlighted in grey, indicate the load cells that are used in most experiments.

Special features of BM1

1. Maximum displacement ca. 2 mm.
2. Lower 20 mm support is laterally movable \Rightarrow K_{II} -load.
3. Correction measurement (machine compliance) with equal support distances.
4. Simultaneous electric loading of sample is possible (tested up to 14 kV and 500 V/mm, respectively).

Special features of BM2

1. Maximum displacement ca. 20 mm.
2. Maximum range of position encoders ca. 116 μm .
3. Measurement of displacements $> 116 \mu\text{m}$ with pulse generator of step motor.
4. Loading speed v : $0 \mu\text{m/s} < v \leq 10 \mu\text{m/s}$.
5. Determination of crack length either optically on video image or automatically via the compliance method.

Appendix C (Compilation of student works)

Additional information about the mechanical properties and electronics of the bending machines as well as concerning the machine control and data acquisition program written in LabView can be found in the following selected student works. These works were all conducted at the Institute of Advanced Ceramics of the TUHH. The abbreviations BM1 and BM2 (bending machine) indicate the testing machine(s) used in these works. BM1 was the first prototype and BM2 an advanced and mechanically optimized model. However, it was only possible to simultaneously apply mechanical and electric loads with the first BM1 machine. With BM1, the mechanical, electric, and piezoelectric compliance of the specimen was recorded at the same time in one measurement as a function of the crack length with two advanced modulation techniques. (Note: "electric compliance" is the capacitance.) The BM2 machine applies partial unloading to determine the mechanical compliance. In the work of E. Zegarra Berodt, the bending machines were not used; nevertheless, this work is also included because 3-point bending tests were performed using a nanoindenter.

- Florian Gehrig: Bruchmechanische Untersuchung am leitenden Riss in PZT. Diplomarbeit, BM1 (2004)
- Peik-Christian Witte: R-Kurvenverhalten von Mikrolaminaten auf Si_3N_4 -Basis. Große Studienarbeit, BM1 (2005)
- Felix Hackbarth: Automatisierte R-Kurven-Messung. Diplomarbeit, enthält Programmierung des LabView-Programms zur Maschinensteuerung und Datenaufnahme, BM1 (2007)
- Claudia Neusel: Bruchversuche an mechanisch gepolten PZT-Proben unter elektromechanischer Last. Studienarbeit, BM1 (2007)
- Henning Krohn: Optimierung eines 4-Punkt-Biegeprüfstandes zur Bestimmung von R-Kurven an keramischen Prüfkörpern. Studienarbeit, BM1/BM2 (2008)
- Hüseyin Özcoban: Messung der intrinsischen Bruchzähigkeit und R-Kurve von Strukturkeramiken mittels einer neu entwickelten Modulationstechnik. Diplomarbeit, BM1 (2008)
- Kun Yang: Weitere Optimierung einer 4-Punkt-Biegeapparatur zur automatischen R-Kurven-Messung. Studienarbeit, BM1 (2008)

- Vitalij Salikov: Untersuchungen zum Verlauf der Rissfront in Keramiken unter stabilem Risswachstum. Große Studienarbeit, BM1 (2009)
- Hüseyin Özcoban: Hochpräzise R-Kurven- und schnelle v-K_I-Kurven-Messung an Keramiken mittels einer steifen, computergeregelten Biegeapparatur. Dissertation, BM2 (2012)
- Greg M. Jaeger Chong: Development and Testing of a Control Program for Automated Stable Crack Growth in R-Curve Measurements. Master's Thesis, BM2 (2014)
- Juan Eduardo Navarro Heredia: Optimizing of a Computer-Controlled Testing Machine and Validation of its Operation with a Modified Schwickerath-Test. Master's Thesis, BM2 (2015)
- Maria Kröchert: Schnelle v-K-Kurven-Messungen an Glas im Biegeversuch. Projektarbeit, BM2 (2015)
- Judith Marie Undine Siebert: Die makroskopischen mechanischen Eigenschaften von Rinderzahnschmelz unter Druck. Bachelorarbeit, BM2 (2016)
- Jannik Krivohlavek: Optimierung einer neuartigen Biegemaschine für schnelle v-K-Kurven-Messungen und Validierung an Glas und Si₃N₄-Materialien. Bachelorarbeit, BM2 (2016)
- Alexander Lenhardt: Direkte Ermittlung von R-Kurven und v-K-Kurven am Beispiel von Aluminiumoxid. Masterarbeit, BM2 (2019)
- Eduardo Zegarra Berodt: Applicability of the Bending Method Performed with a Nanoindenter for Samples of Micrometer Scale. Masterarbeit, Nanoindenter (2020)
- Fynn Pieper: Zeitlich hochaufgelöste Messung und Analyse von Ladungs- und Kraftverlauf während des instabilen Bruchs von polarisiertem PZT. Projektarbeit, BM1 (2021)

All student works are internally available as full text (PDF, → Dr. Jasmin Koldehoff, TUHH). Additional information about the experimental setup and about the different kinds of experiments conducted with the bending devices is provided in the references [1–3, 7–16].

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