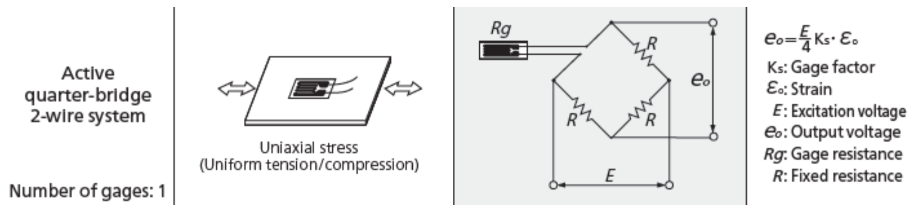


Figure 1: Strain gauge configuration

Strain Gauges

Strain gauges are made use throughout the whole experimental procedure.

The strain gauges, by principle, work inside a Wheatstone bridge. One of the simplest configurations of strain gauges is what is called an active quarter-bridge 2-wire system. [1] (See Figure 1) This is also the configuration we use for the strain gauge on the center of our specimen for the uncracked tests. Here, R_g is the resistance of the strain gauge placed on the specimen, which is plugged to the strain amplifier by two cables coming out of it. (See Fig. **??**) The other 3 resistances (with equal resistances of R) of the Wheatstone bridge are inside the strain amplifier device. Excitation voltage E is given to the circuit by the strain amplifier. Compression or tension of the specimen causes the resistance of R_g to change and creates a change in the output voltage e_0, which is amplified and read by the strain amplifier.

The strain amplifier can work in two modes depending on the required sensitivity of the measurement: either $50mV/V$ or $5mV/V$. First one means that $1V$ of change in the output voltage corresponds to 1% strain whereas the second one amplifies 1% strain to a $10V$ of change. For materials requiring more sensitive strain measurements such as a steel bar, $5mV/V$ is more suitable while for a more ductile aluminum sheet $50mV/V$ is sensitive enough to measure the change in strain. Keeping in mind that strain is a unitless parameter, 1% strain basically means a strain of 0.01. Therefore, if we set the amplification factor of the strain gauge couple on our steel pretensioning bar to $5mV/V$, multiplying the read voltage value with $0.01/10 = 0.001$ would result the strain the bar is going through.

The number and placement of the strain gauges modify the Wheatstone bridge and changes the meaning of the output voltage in terms of strain. This point will be made more clear under the next section.

If the gauge factor of the strain gauge is different from that of the strain amplifier, the measured strain, ε_0, needs a correction to obtain the real strain, ε. This is the case for our setup.

$$\varepsilon = \frac{k_{amp}}{k_s}\varepsilon_0 \tag{1}$$

where k_{amp} is the gauge factor of the strain amplifier. It is equal to 2.00 for the strain amplifier we use in our laboratory. k_s, on the other hand, is 2.12 for the strain gauges we use.

Strain Gauge Couple on a Bar

The torsion bar in the setup is likely to undergo a bending strain. Therefore, two strain gauges are placed on the bar to be able to differentiate the effect of the bending strain from the axial strain, the latter being the important parameter for us. In this section, it will be investigated why only one strain gauge is not enough to obtain the axial strain of a bent part and how two of them can achieve this.

Figure 2 shows three exemplary loading cases, I, II and III, of the bar. Initially, the machine does not apply any force on the specimen in the vertical direction. Hence, P is zero. On the other hand, there is a $\mathrm{P}_{\mathrm{pretension}}$ given in the transverse direction via the torsion bar, i.e. initially $\mathrm{P}_{\mathrm{transverse}} = \mathrm{P}_{\mathrm{pretension}}$. In fact, Figure 2a illustrates the readings from both of the strain gauges as a result of this pretension. Note that there is a linear relation between force and strain in the linear elastic region of the material we are working with. Therefore, we have illustrated the lines indicating forces on the top and the bottom of the cross section whose lengths are proportional to the magnitude of the force but we have only quantified them with the strain gauge voltage values since voltage readings will be linearly proportional to the strain and the force. The pretension load is the one we intentionally want to apply whereas the pure bending component occurs as an unwanted result of it. We can only read their sums from the strain gauges. Figure 2b, on the other hand, shows what would be the strain gauges readings in case we start the cyclic loading and the bending is assumed to remain the same. In this case, the transverse load will increase as a result of the restricted displacement in the transverse direction and read values of both of the strain gauges will increase with the same slope as the machine loads the specimen.

There are some conclusion to be drawn from these examples. First of all, mean of the two strain gauge readings (green dashed lines in Figure 2b) correspond to the axial force the bar experiences in the transverse direction.

$$SG_{axial} = SG_{mean} = \frac{SG_1 + SG_2}{2}$$

where SG indicates the strain gauge readings in volts. This proves that if we read the strain from two different strain gauges placed on the opposite sides of the same bar, we can eliminate the bending of the bar by taking the mean of the readings.

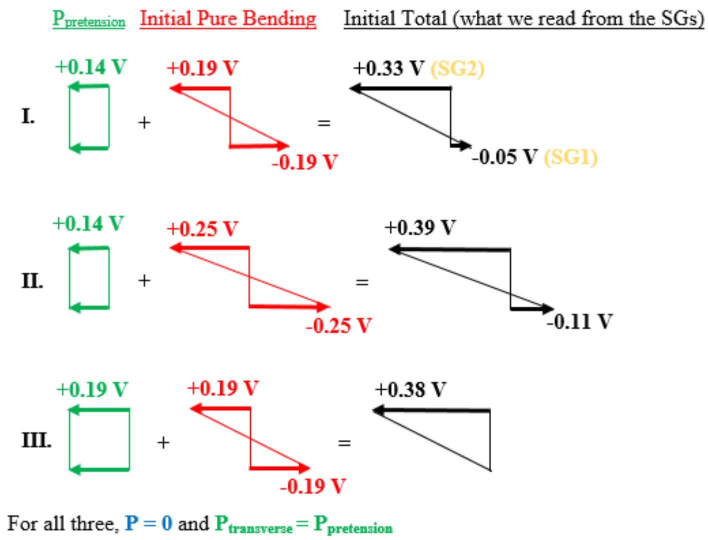
On the other hand, the difference between the readings of each of the strain gauges and their mean (red lines in Figure 2b) correspond to the size of the pure bending component of the strain.

$$SG_{bending} = |SG_{1,2} - SG_{mean}|$$

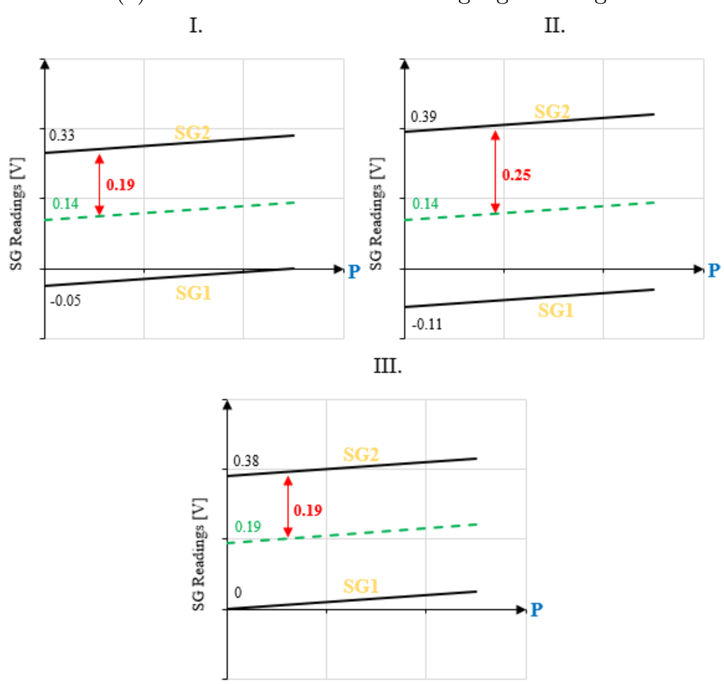
Next, we will assume a load state for the case I of Figure 2 at a forward time instance, ii, in comparison with the initial state, i. This time, not only a change in the axial component but also a change of bending is assumed. (See Figure 3) It is clear that if the bent of the bar is enhanced or reduced, the slopes of the strain gauge reading lines differ from each other. More importantly, one of the readings increasing while the other decreasing means that the bending is greater than the axial loading. If the magnitude of increase in the axial loading was greater than the increase of the bent, values of both readings would increase.

These findings provide us the knowledge of what is happening when two strain gauges are placed on the bar and read separately. The most important outcome is to know that we should take their means to assess the transverse response to the axial cyclic loading.

In the bar calibration test, we read the strain gauges separately and used the findings of this section. However, in the uncracked specimen test setup, since we did not have enough input ports in the machine for all the strain gauges and LVDT we have, we had to design a Wheatstone bridge that reads two strain gauges on the bar at the same time and eliminates the bending effects by taking their mean. We found the configuration shown in Figure 4 competent for this purpose. We did not break this configuration afterwards and used it for fatigue tests too.

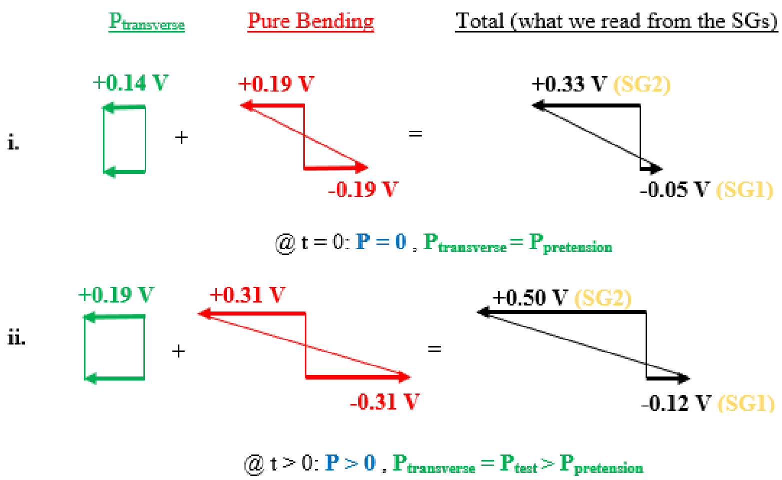


(a) Initial load state and strain gauge readings

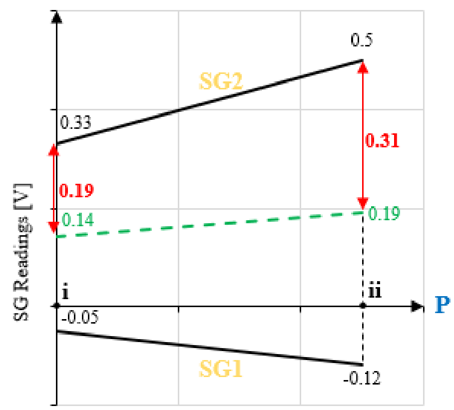


(b) Readings as the transverse load increases with the assumption that bending remains the same

Figure 2: Three exemplary cases of loading on the bar and the change in the strain gauge readings



(a) Load state and strain gauge readings at two instances



(b) Readings as the axial transverse load increases along with the bending

Figure 3: Change of load state and strain gauge readings of the bar between 2 different exemplary time instances during a test

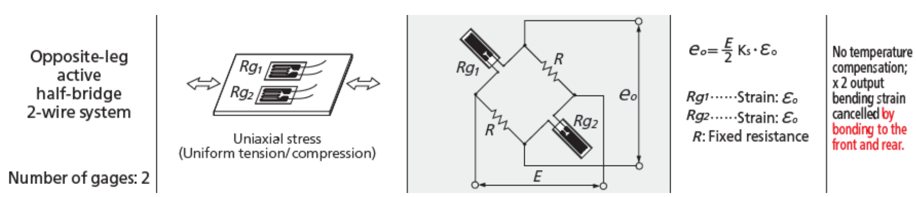


Figure 4: Wheatstone bridge of the strain gauges used on the bar

Bar Calibration

Relating the strain gauge readings on the bar to the force acting on it requires a procedure which is simply called as calibration. Before being assembled with the rest of the setup components, the torsion bar underwent through this calibration test after the strain gauges are placed on it. For the calibration test, the bar is clamped to a tensile test machine and starting from the unloaded condition, load is increased gradually up to a magnitude of 50 kN and then taken back to zero. Note that this is below yield stress and we expect linear elastic behaviour. Meanwhile, the voltages are read and recorded from the strain gauges. Corresponding load and displacement values at each data point are measured and recorded by the machine.

Enough runs are made to have a sufficient number of curves to obtain accurate values. 3 of the tests are done after the bar is rotated 90 degrees to account for the changes when the strain gauges are placed orthogonally to the clamps of the test machine. In all of the calibration tests, both of the strain gauges were connected with the configuration shown in Fig. 1. Hence, we had two separate readings from the two strain gauges. We averaged them to have a single averaged curve for each run. Then the curves of all runs are averaged to give the resultant calibration curve shown in Figure 5 with the blue dashed line, labeled as the Mean.

A few outlier runs are not taken into account as well as one that increases dramatically in the beginning due to clamping issues. After all, we were able to make use of 5 consistent lines whose mean provided us the ultimate calibration curve.

Thanks to this calibration curve, we will be able to relate the strain value read from the strain gauges on the bar during the experiments to the response it gives in terms of load.

Linear Voltage Differential Transformers

Linear voltage differential transformer (LVDT) is an absolute measuring device that converts linear displacement into an electrical signal through the principle of mutual induction.

LVDT calibration process is basically placing gauge blocks with known thick-

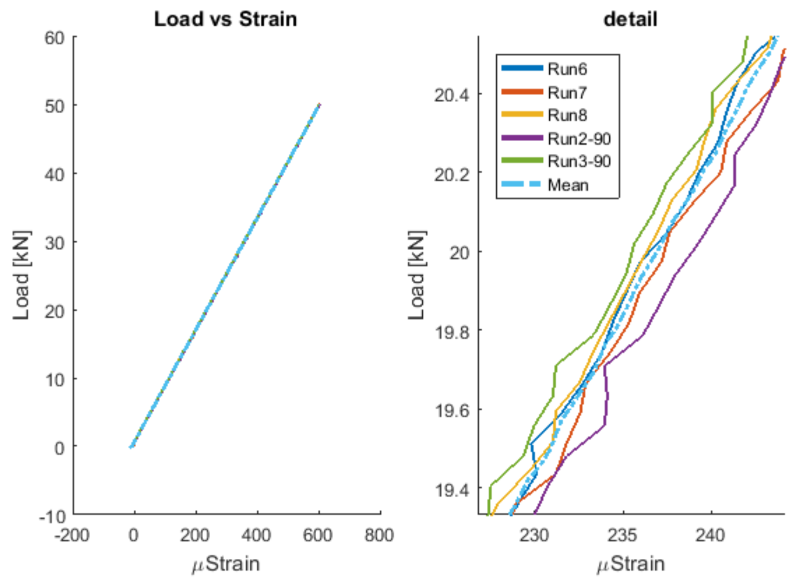


Figure 5: Calibration bar of the steel torsion bar

ness under the push rod (a non-ferromagnetic shaft) to see how the LVDT reading changes for that amount of displacement. (See Figure 6) Since there is a linear relationship between the displacement change and the voltage read from the LVDT, a coefficient can be found which can be multiplied by any reading from LVDT to result in the displacement.

Since there may be small amount of surface defects on the gauge blocks and the results may vary according to the way the gauge blocks sit on the defective surface of the hydraulic piston, we place the gauge blocks in two different alignments and take the average of the results. Additionally, since the response of LVDT may differ in different ranges of displacements, we take results from gauge blocks of different thickness. Using a 1.005 mm gauge block and a 2 mm one satisfies the displacement range we are working with.

It is seen that placing a 1.005 mm thick gauge block in two different alignments increased the voltage read from the LVDT, averagely, by 1.042 V, which is equal to $1.005/1.042 = 0.9645$ mm/V. The average result of placing a 2 mm thick gauge block is found as 0.9790 mm/V. Total average of the two blocks gives 0.9718 mm/V, which is the coefficient we are using throughout our calculations.

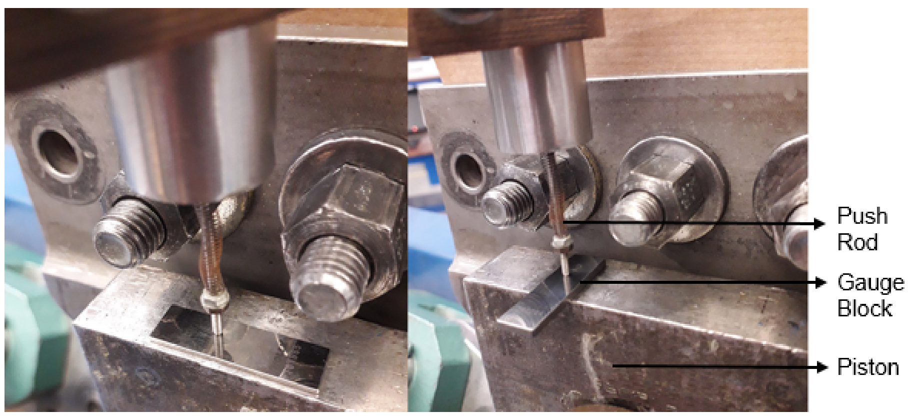


Figure 6: LVDT calibration including the two different alignments of the gauge block

Bibliography

[1] *Strain Gages*. https://www.kyowa-ei.com. KYOWA Electronic Instruments Co.,Ltd. Mar. 2018.