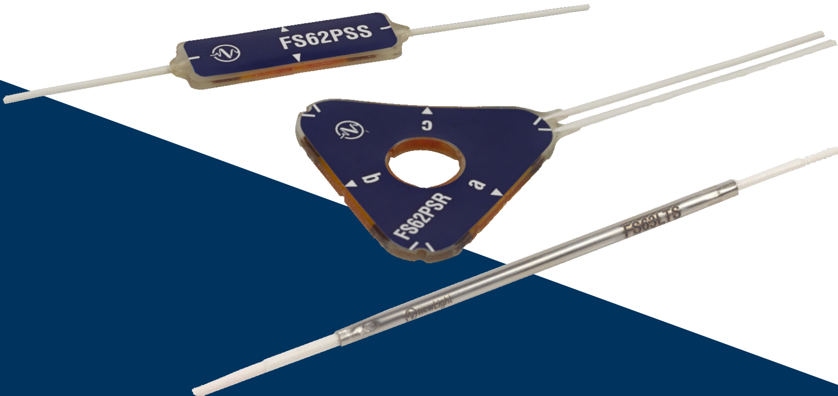
ENGLISH

Mounting Instructions



FS62PSS, FS62PSR, FS63LTS

Patch Strain, Patch Rosette and Laboratory Temperature Sensors

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1 GENERAL INFORMATION

The following instructions refer to the installation procedure of FS62PSS Patch Strain Sensors, FS62PSR Patch Strain Rosette and FS63LTS Laboratory Temperature Sensors. These sensors can be delivered individually or in arrays of sensors preassembled at HBK FiberSensing facilities.

Material Numbers		
Strain Sensors	**Strain Rosettes**	**Temperature Sensors**
K-FS62PSS	K-FS62PSR	K-FS63LTS
1-FS62PSS-1510	1-FS62PSR-3505	1-FS63LTS-1515
1-FS62PSS-1520	1-FS62PSR-3520	1-FS63LTS-1525
1-FS62PSS-1530	1-FS62PSR-3535	1-FS63LTS-1535
1-FS62PSS-1540	1-FS62PSR-3550	1-FS63LTS-1545
1-FS62PSS-1550	1-FS62PSR-3565	1-FS63LTS-1555
1-FS62PSS-1560	1-FS62PSR-3580	1-FS63LTS-1565
1-FS62PSS-1570		1-FS63LTS-1575
1-FS62PSS-1580		1-FS63LTS-1585
1-FS62PSS-1590		1-FS63LTS-1595
Sensor Arrays		
K-FS76BRD		

2 INSTALLATION PROCEDURE

2.1 List of materials

Included material		
FS62PSS	**FS62PSR**	**FS63LTS**
Sensor	Sensor	Sensor
Teflon installation aid	Teflon installation aid	
Teflon foil	Teflon foil	
Pressure pad (one per set)	Pressure pad (one per set)	

Needed equipment
Deburring machine (optional)

Needed material
Glue. Recommended HBK: 1-Z70, 1-X60 or 1-X280
Sandpaper
Surface cleaning agents. Recommended HBK: 1-RMS1 or 1-RMS1-SPRAY
Tissues. Recommended HBK: 1-8402.0026
Polyimide drafting tape. Recommended HBK: 1-KLEBEBAND
Protection. Recommended HBK: 1-ABM75 and/or AK22

2.2 FS62PSS Patch Strain Sensor

2.2.1 Preparation of the installation area

The surface of the measurement object must be cleaned and regular when installing the optical strain gauges or sensors.

If there are protection layers applied on the material, such as paint or rust, deburr (*Fig. 2.1*) or sand (*Fig. 2.2*) the surface to remove them ensuring that the surface does not become irregular.

Fig. 2.1 Removing paint and rust with a deburring machine

Fig. 2.2 Removing paint and rust with sand paper

Clean the surface using an appropriate cleaner degreaser (RMS 1 is suggested) and non-woven tissues (Fig. 2.3 and Fig. 2.5).

Repeat the cleaning process until the tissue comes out clean.

Fig. 2.3 *Using RMS1 cleaner and nonwoven tissues*

If the material is free of protective layers and very smooth, there is still the need to roughen the surface with the sanding paper (e.g. with 180 grain) using circular movements (*Fig. 2.4*).

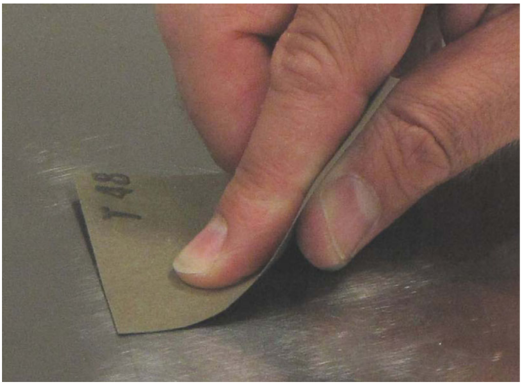

Fig. 2.4 *Roughening the surface of the measuring object*

The surface needs then to be cleaned again ensuring that neither dust nor grease is present in the bonding area.

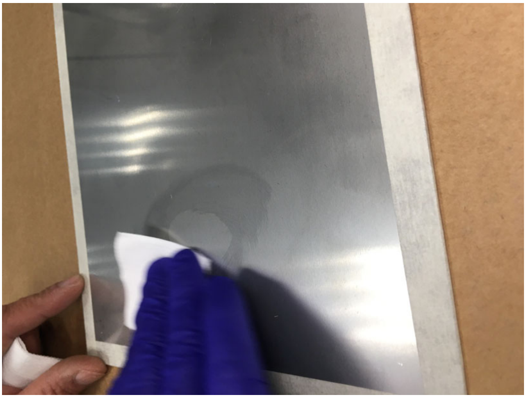

Fig. 2.5 Cleaning the surface

The final wiping movements should always be performed in the same direction until the last tissue comes out clean.

2.2.2 Marking the measuring point

Define the alignment of the sensor considering the measurement direction and the sensor's guides.

Fig. 2.6 FS62PSS Sensor alignment markings

Tip

Use a sharp tool or a pen, depending on the surface material, to mark the sensor position.

Tip

Ensure your hands and used tools are clean to prevent contamination of the gluing area.

The length of the marking line should be approx. 60 mm in the measurement direction. A vertical marking line, approx. 40 mm long, must be drawn to indicate the center of the sensor, *see Fig. 2.7*. Interrupt both lines at the sensor's gluing area.

Fig. 2.7 Marking the sensor position

2.2.3 Positioning the sensor

Remove the optical sensor from the protective wallet in the box and peel off the Teflon protective foil from the installation side of the sensor.

Tip

Save the Teflon protective film to use it later during the gluing phase.

Then transfer the sensor securing it by the Teflon installation aid attached to the marked measuring point. After positioning the sensor aligned with the designed cross, apply a 10 cm long polyimide adhesive tape (1-KLEBEBAND) on top of the Teflon installation aid, without touching the sensor, to secure it to the measuring object (*Fig. 2.8*)

Fig. 2.8 Aligning and placing the FS62PSS

The next step is not mandatory, but it is recommended so that the adhesive does not leak.

Apply another 10 cm long polyimide adhesive tape (1-KLEBEBAND) on the other side of the sensor, a few millimeters away from the sensor and aligned with its longer edge (*Fig. 2.9*).

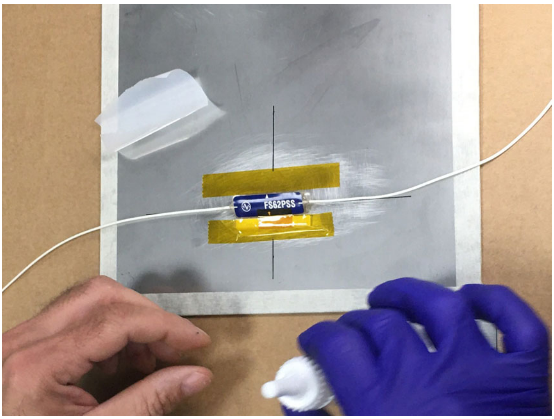

Fig. 2.9 Applying an adhesive mask

2.2.4 Gluing the sensor

The following instructions are prepared based on the Z70 adhesive, which is a cyanoacrylate glue. The sensor can also be installed with other adhesives. Usage instructions of the glues must be taken into consideration and the following instructions adapted in accordance.

The following table presents the main characteristics and applications of the preferred HBK glues:

Adhesive	Curing	Operating temperature	General comments
Z70	@20°C: 1min	-55°C to 100°C[1] -55°C to 120°C[2]	Measurements possible after 30 minutes; Constant pressure (by thumb) and 30 to 80% air humidity needed during installation.
X60	@20°C: 10min	-200°C to 60°C[1] -200°C to 80°C[2]	Measurements possible after 30 minutes; Stiff glue; Not suited for dynamic bending; Thin layer between sensor and surface must be ensured during installation.
X280	@10°C: 36h @20°C: 8h @65°C: 2h @95°C: 1h	-200°C to 200°C[1] -200°C to 280°C[2]	Recommended for high fatigue life applications.

1) For zero point related measurements
2) For dynamic measurements

Prepare the Z70 adhesive and have the small piece of Teflon foil (removed from the sensor when unpacking) ready at hand.

Flip the FS62PSS sensor using the Teflon installation aid as a hinge for the optical sensor as shown in *Fig. 2.10*. Place three drops of Z70 adhesive on the area that will receive the sensor, without allowing the Z70 bottle to touch the surface.

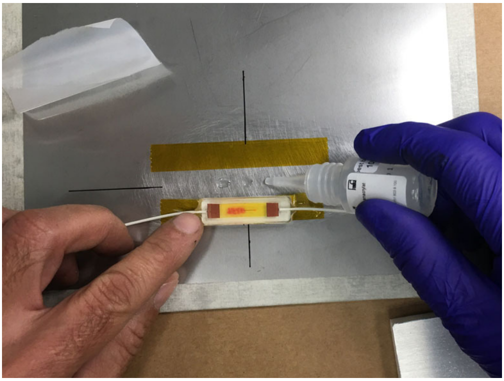

Fig. 2.10 Folding over the FS62PSS and application of Z70 adhesive

Fold the sensor quickly back down over the adhesive. Cover with the prepared Teflon foil as an intermediate layer and apply pressure to the sensor firmly and evenly for approximately one minute. A pressing pad for pressure distribution is provided to support at this step.

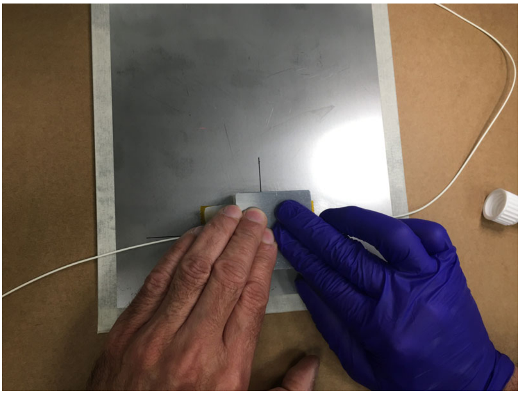

Fig. 2.11 Gluing on the FS62PSS and hardening of the adhesive

After gluing, and if needed, remove any excess Z70 adhesive from the material surface with a nonwoven pad.

The Z70 adhesive requires another ten minutes to harden after gluing. If you have implemented the strain relief as described below, you can then remove the adhesive strips, otherwise wait for approx. ten minutes more. You can then remove all adhesive strips and the installation aid. Where possible, peel the adhesive strips off at a small angle and flat to the surface (*Fig. 2.12*).

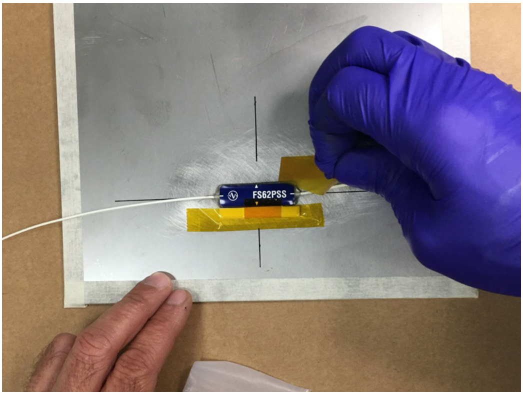

Fig. 2.12 Removing the fixing adhesive strips

Then carefully remove the Teflon installation aid (*Fig. 2.13*).

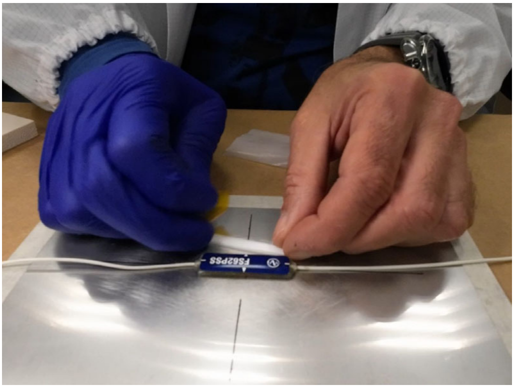

Fig. 2.13 Removing the Teflon installation aid

In this last step, remove any remaining adhesive residues located under the Teflon installation aid, using a nonwoven pad.

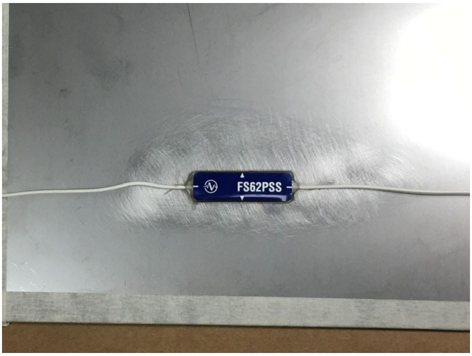

Fig. 2.14 Completed installation of the optical strain sensor

Please also note the information on hardening times in the Z70 Installation manual.

2.3 FS62PSR Patch Strain Rosette

2.3.1 Preparation of the installation area

For the installation of the FS62PSR Patch Strain Rosette, the surface must be clean and without irregularities. Please follow the procedures as described for FS62PSS on *section 2.2.1 on page 5*.

2.3.2 Marking the measuring point

The FS62PSR Rosette has three FBGs in a 0º/60º/120º position. The alignment of each FBG is evidenced by the sensor guides present at each corner of the rosette, which are defined as directions "a", "b" and "c", as shown in *Fig. 2.15*.

Start by drawing the marking cross, in a similar way to the described in *section 2.2.2*, considering one of the FBG alignments, for example “a”, and its perpendicular.

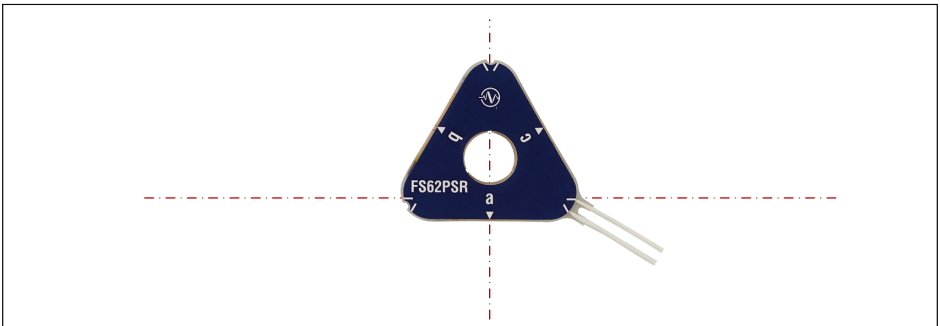

Fig. 2.15 FS62PSR sensor alignment markings

2.3.3 Positioning the sensor

Position the optical rosette on the marking cross using the Teflon installation aid.

Align the desired direction, for example “a”, with the horizontal marking. Refer to the white alignment marks present on the sensor label to support on this positioning. Then align the perpendicular direction, for example between the arrow on the “a” direction and the intersection between “b” and “c” direction marks, with the vertical marking.

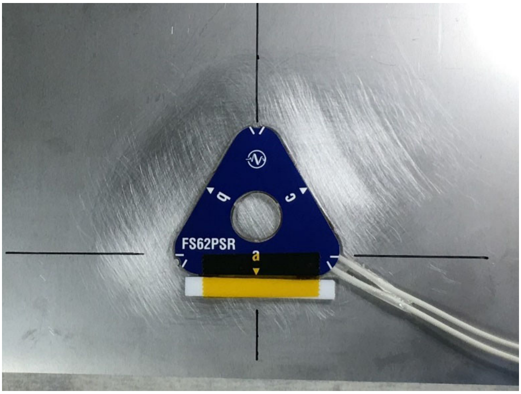

Fig. 2.16 Aligning the optical rosette

It is advisable that an adhesive mask is applied around the sensor position to prevent adhesive from leaking when gluing the FS62PSR. To do this, use two additional strips of polyimide adhesive tape, applying them in parallel to the edges of the optical rosette *(see Fig. 2.17)*.

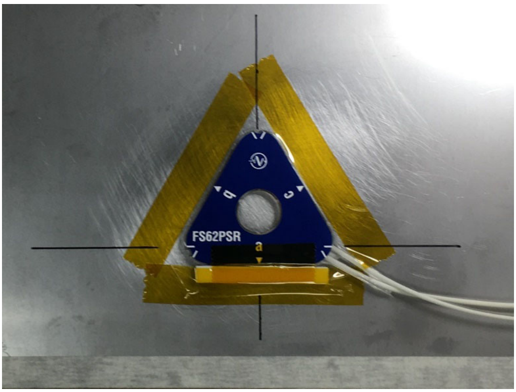

Fig. 2.17 Applying an adhesive mask

2.3.4 Gluing the sensor

As for the FS62PSS Patch Strain Sensor, the following procedures refer to the installation of the FS62PSR Patch Strain Rosette using Z70 superglue. Please refer to *section 2.2.4* “Gluing the sensor” on page 10 for additional information on different adhesives.

Have the Z70 adhesive and the provided piece of Teflon foil ready at hand. Use the Teflon installation aid as a hinge for the optical rosette and fold the rosette back. Place 6 drops of Z70 adhesive in a triangle on the measuring point (under the optical rosette), without allowing the Z70 bottle to touch the surface, *see Fig. 2.18*.

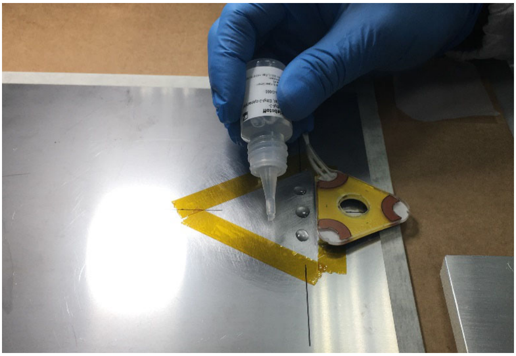

Fig. 2.18 Applying the adhesive

Fold the optical rosette quickly back down over the adhesive. Cover with the prepared Teflon foil as an intermediate layer (*Fig. 2.19*) and apply pressure to the rosette firmly and evenly for approx. one minute e.g. by using a press pad.

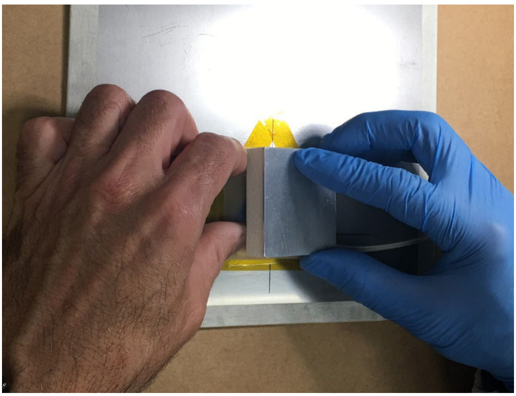

Fig. 2.19 Applying the Teflon foil and pressure pad

Fig. 2.20 Pressing on the rosette for 1 minute

The Z70 adhesive requires another ten minutes to harden after gluing. You can then remove all adhesive tape and the installation aid. Where possible, peel off the adhesive tape at an angle and flat to the surface.

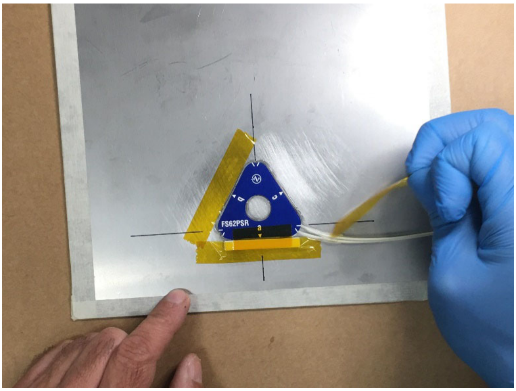

Fig. 2.21 Removing the tape

Then carefully remove the Teflon installation aid, as described for the FS62PSS in *Fig. 2.13 on page 13*.

In this last step, remove any remaining adhesive residues located under the Teflon installation aid using a nonwoven pad. Please also note the information on hardening times in the Z70 Installation manual.

2.4 FS63LTS Laboratory Temperature Sensor

2.4.1 Preparation of the installation area

For the installation of the FS63LTS Laboratory Temperature Sensor, the surface must be clean and without irregularities. Please follow the procedures as described for FS62PSS on *section 2.2.1 on page 5*.

2.4.2 Positioning the sensor

The orientation of the FS63LTS is not of major importance for a correct temperature measurement. It is, however, important that the sensor is placed next to the strain sensors if being used for temperature compensation. Temperature compensation is only effective if the two sensors – strain and temperature – are at the same temperature.

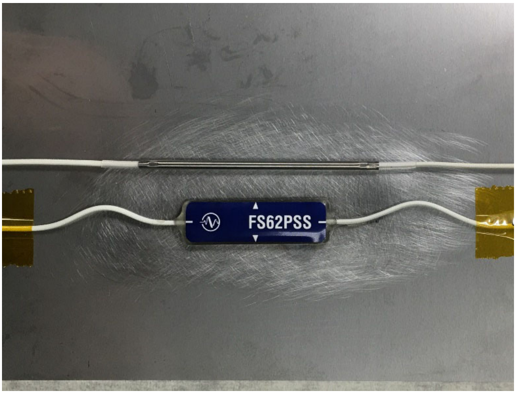

Fig. 2.22 Positioning the temperature sensor

2.4.3 Fixing the sensor

The temperature sensor needs to be fixed with any method that allows a thermal contact between the specimen to measure and the sensor. The easiest way to fix the sensor is to use tape on top of it, for example, polyimide adhesive tape (1-KLEBEBAND), or to use covering agents 1-ABM75 or 1-AK22. It can also be glued to the surface with an adhesive that grants a good thermal contact between the surface and the sensor. However, care must be taken to the fact that the glue should be applied to the center part of the sensor only to ensure that no strain is transmitted to the sensor.

For temperature compensation place the compensation sensor as close as possible to the strain sensor which strain signal needs to be compensated.

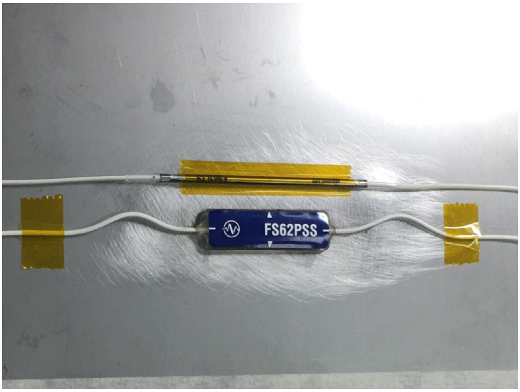

Fig. 2.23 FS63LTS fixed with polyimide tape

2.5 Routing and protecting the cables

Sensor cable should be routed ensuring that cables are not hanging and curvatures are kept within the limits for the used cable.

We recommend that strain relief is provided for the optical fiber *(see Fig. 2.24)*. Lay down the protruding fibers with gentle curves and fix them with polyimide adhesive tape. Alternatively, glue can also be used (for example X60).

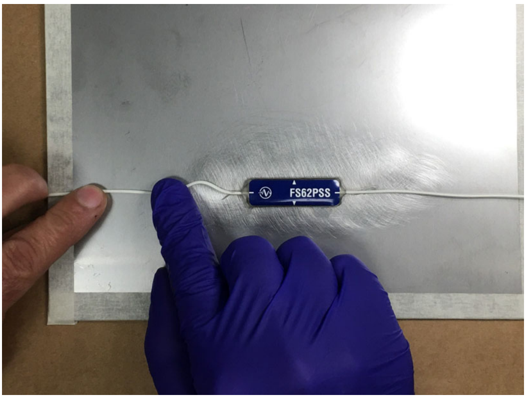

Fig. 2.24 Strain relief for the optical fibers

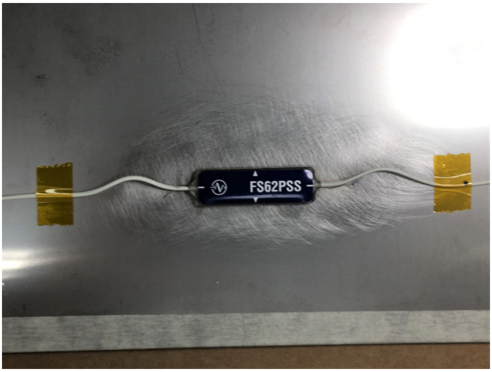

Fig. 2.25 Fixing fiber strain relief with tape

In case there are splice protections, ensure that the splice is also well fixed.

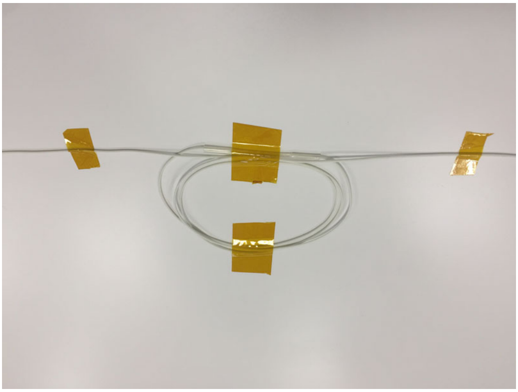

Fig. 2.26 Braided cable routing

For outdoor applications it is also advisable to further protect cable paths against moisture and mechanical damage. This can be achieved either by using cable conduits, or by covering the full length with silicone or other sealing paste (example DP490 from 3M).

Information

The braided cable is suited for laboratory installations in controlled environments. It can withstand an extended temperature range, but is not fully protected for mechanical damage. In case the sensors are used in harsh environments, further protection of the cables is recommended (using plastic tubes, conduits or covering the cables with protecting material).

2.6 Protecting the sensors

The FS62PSS, the FS62PSR, and the FS63LTS are sensors designed for laboratory applications. Nevertheless they can be used in other environments if correctly protected.

Sensors should be protected against humidity effects with the covering agents AK22 and ABM75.

First cover all the adhesive residues (Z70 in this case), left over from gluing, generously with the covering putty. Carefully press the putty towards the sensor from all sides (*Fig. 2.27*)

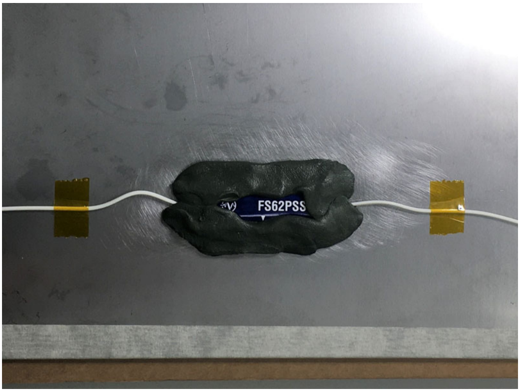

Fig. 2.27 Covering the sensors edges with AK22

Always include some AK22 below the cables to ensure complete coverage. This should be done next to the sensor, as well as on the interface of the remaining protective layers (*Fig. 2.28*).

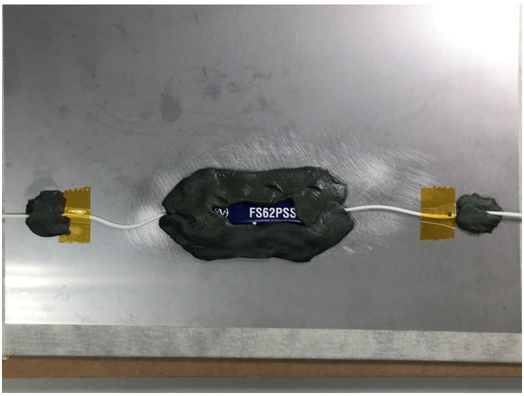

Fig. 2.28

Cut a piece of the covering foil ABM75 (*Fig. 2.29*), large enough to cover the sensor area (a single sensor or several close to each other – e.g. one FS62PSS and one FS63LTS for temperature compensation) and place it over the sensor.

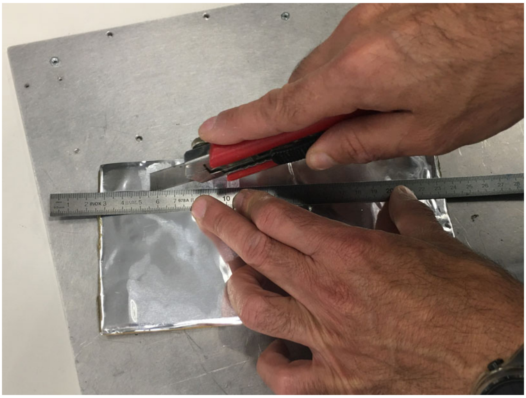

Fig. 2.29 Cutting ABM75 to fit the sensor area

Press the covering foil around its edges with a stiff element to tighten into the surface of the measurement object.

Notice

Pay extra care to not apply this pressure over the cable area as it can damage the fibers compromising the sensor reading. On the cable area this sealing should be ensured with your fingers.

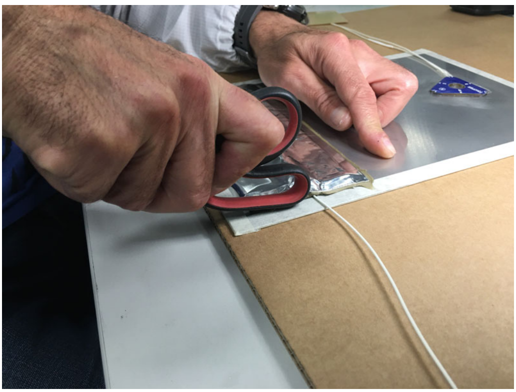

Fig. 2.30 Applying and pressing down the covering foil ABM75

Fig. 2.31 Completely covered measuring point

3 SENSOR CONFIGURATION

3.1 Sensors documentation

Calibrated HBK FiberSensing Sensors are delivered with a Calibration Sheet. Remaining sensors are delivered with a sensor Characteristic Sheet that contains important information for sensor configuration.

In the case sensors are delivered in arrays of pre-assembled sensors, a resume table with the relevant calibration information is provided in alternative.

Within the sensor's packing this installation instructions document is delivered in a printed version. Installation instructions can also be downloaded from HBK website (www.hbm.com).

3.2 Measurement computation

3.2.1 Temperature

The calculations that should be performed for converting a wavelength measurement into temperature are the shown in *Fig. 3.1*. The temperature value measured with a temperature sensor is given by a second order polynomial equation with coefficients obtained from the sensor calibration.

$$T = S_2(\lambda - \lambda_0)^2 + S_1(\lambda - \lambda_0) + S_0$$

Fig. 3.1 Temperature computation formula

Where

- T is the measured Temperature in °C
- λ is the measured Bragg wavelength of the temperature sensor in nm
- λ_0 is the Bragg wavelength of the temperature sensor at reference temperature in nm
- S_0 is the zero order calibration factor (reference temperature) in °C
- S_1 is the first order calibration factor in °C/nm
- S_2 is the second order calibration factor in °C/nm^2

When operating with catman® the values λ_0, S_0, S_1 and S_2 should be filled on the menu for temperature sensors configuration.

3.2.2 Strain

Strain sensors are not calibrated sensors. The characteristic sheet delivered with the sensor presents the sensor data for correct strain computation.

For the fiber Bragg grating strain sensors, wavelength variation including the effect of temperature is given by the equation shown in *Fig. 3.2*.

$$\frac{(\lambda - \lambda_0)}{\lambda_0} = k \cdot \left(\varepsilon_{Load} + (TCS + CTE) \cdot (T - T_0)\right) \cdot 10^{-6}$$

Fig. 3.2 *Wavelength variation of a FBG strain sensor due to strain and temperature effects*

Where

- λ is the measured Bragg wavelength of the strain sensor in nm
- λ_0 is the Bragg wavelength of the strain sensor at the reference instant in nm
- k is the strain k factor of the strain sensor, dimensionless
- ε_{Load} is the mechanical strain applied to the structure in µm/m
- *TCS* is the temperature cross sensitivity of the strain sensor in (µm/m)/°C
- *CTE* is the coefficient of thermal expansion of the material of the specimen the strain sensor is attached to in (µm/m)/°C
- T-T_0 is the difference between the actual temperature and the temperature at the reference instant in °C

Measurement with no compensation

If no temperature compensation is required the strain computation can be done as shown in *Fig. 3.3*.

$$\varepsilon = \frac{(\lambda - \lambda_0)}{k \cdot \lambda_0} \cdot 10^6$$

Fig. 3.3 *Simple strain computation formula (without temperature compensation)*

Where

- ε is the measured strain in µm/m
- λ is the measured Bragg wavelength of the strain sensor in nm
- λ_0 is the Bragg wavelength of the strain sensor at the reference instant in nm
- k is the strain k factor of the strain sensor, dimensionless

Measurement with temperature compensation using a temperature sensor

Calculating compensated strain, in µm/m, using a temperature sensor is straightforward as the output of a temperature sensor is a temperature value in °C. The calculation is depicted in *Fig. 3.4*.

$$\varepsilon_{Load} = \frac{(\lambda - \lambda_0)}{k \cdot \lambda_0} \cdot 10^6 - (TCS + CTE) \cdot (T - T_0)$$

Fig. 3.4 Strain computation with temperature compensation using a temperature sensor

Where

- ε_{Load} is the mechanical strain applied to the structure in µm/m
- λ is the measured Bragg wavelength of the strain sensor in nm
- λ_0 is the Bragg wavelength of the strain sensor at the reference instant in nm
- k is the strain k factor of the strain sensor, dimensionless
- *TCS* is the temperature cross sensitivity of the strain sensor in (µm/m)/°C
- *CTE* is the coefficient of thermal expansion of the material of the specimen the strain sensor is attached to in (µm/m)/°C
- T is the actual temperature measured by the temperature sensor used for compensation in °C
- T_0 is the temperature measured by the temperature sensor used for compensation at the reference instant in °C

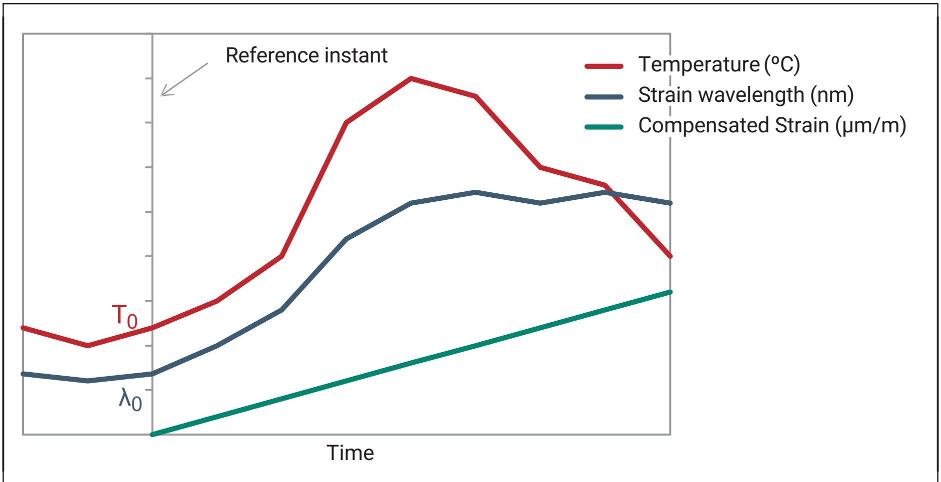

Fig. 3.5 Reference instant for temperature compensated strain measurement when using a temperature sensor for compensation

Measurement with temperature compensation using a compensation element

Strain measurement can also be correctly compensated using a compensation element based on FBG technology. Different approaches can be used:

- a temperature sensor without calibration certificate
- a strain sensor installed on a strain-free area of the same material
- a strain sensor installed on a strain-free material with a known CTE

The computation of strain can then be performed using the equation from *Fig. 3.6*.

$$\varepsilon_{Load} = \frac{\lambda - \lambda_0}{k \cdot \lambda_0} \cdot 10^6 - \frac{\lambda_{Tc} - \lambda_{0_{Tc}}}{\lambda_{0_{Tc}}} \cdot \frac{(TCS + CTE)}{TCF}$$

Fig. 3.6 Strain computation with temperature compensation using an FBG compensation element

Where

- ε_{Load} is the mechanical strain applied to the structure in µm/m
- λ is the measured Bragg wavelength of the strain sensor in nm
- λ_0 is the Bragg wavelength of the strain sensor at the reference instant in nm
- *k* is the strain k factor of the strain sensor, dimensionless
- λ_{TC} is the measured Bragg wavelength of the compensation element in nm
- $\lambda_{0\,TC}$ is the Bragg wavelength of the compensation element at the reference instant in nm
- *TCS* is the temperature cross sensitivity of the strain sensor in (µm/m)/°C
- *CTE* is the coefficient of thermal expansion of the material of the specimen the strain sensor is attached to in (µm/m)/°C
- *TCF* is the temperature compensation factor of the compensation element in (µm/m)/°C. For an uncalibrated temperature sensor this value is given on the sensor's characteristics sheet. For a strain sensor attached to a specific material TCF can be calculated as shown in *Fig. 3.7*.

$$TCF = (5.7 + k \cdot CTE_{TC})$$

Fig. 3.7 Temperature compensation factor computation

Where

- *k* is the strain k factor of the strain sensor attached to the temperature compensation element, dimensionless
- CTE_{TC} is the coefficient of thermal expansion of the material of the temperature compensation element in (µm/m)/°C

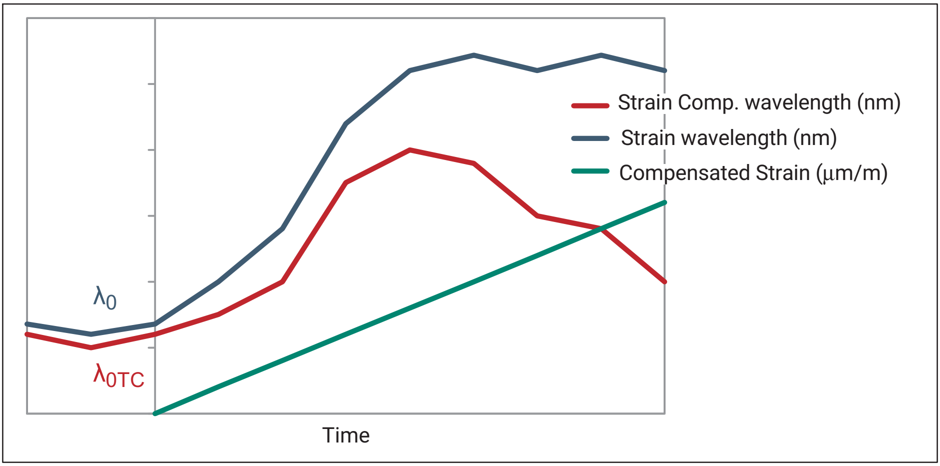

Fig. 3.8 *Reference instant for temperature compensated strain measurement when using an FBG compensation element*

Measurement with bending moment correction

When measuring on an element using a sensor that is far away from the attachment surface there may be an "error" on the measurement because the distance between the measuring point/alignment and the neutral axis is different to the distance between the installation surface and the neutral axis.

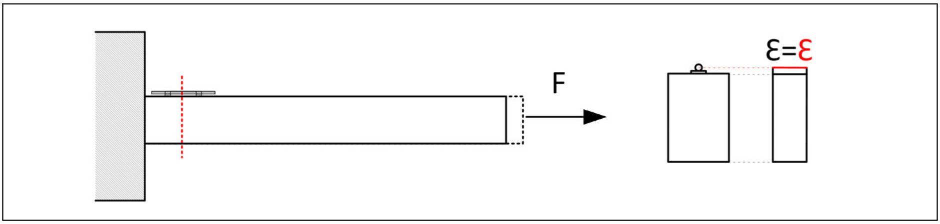

Fig. 3.9 *Strain on pure axial deformation*

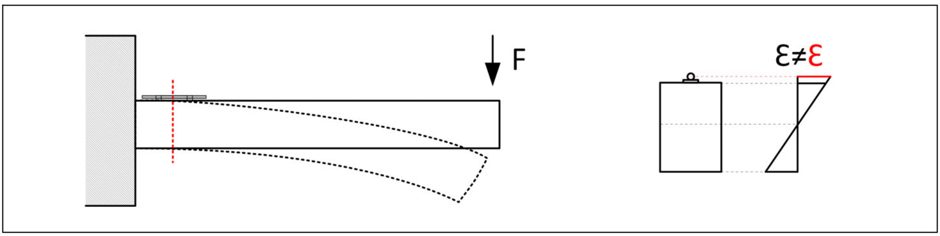

Fig. 3.10 *Strain on pure bending moment*

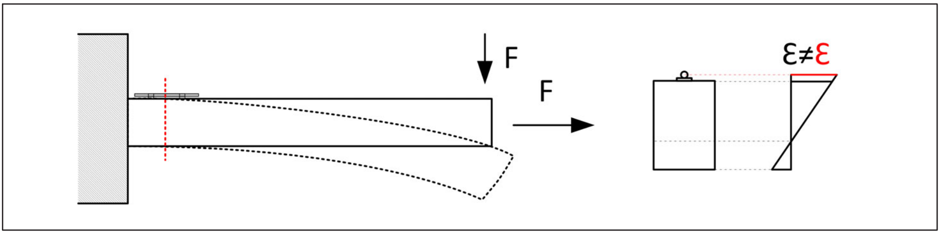

Fig. 3.11 *Strain on axial load and bending moment*

This becomes of high importance when the distance between the sensing element on the sensor to the attachment surface is relevant, or the measuring object is very thin. This distance on the FS62PSS Patch Strain Sensor and for the FS62PSR Patch Strain Rosette is 0.25 mm (h_2 on *Fig. 3.11*).

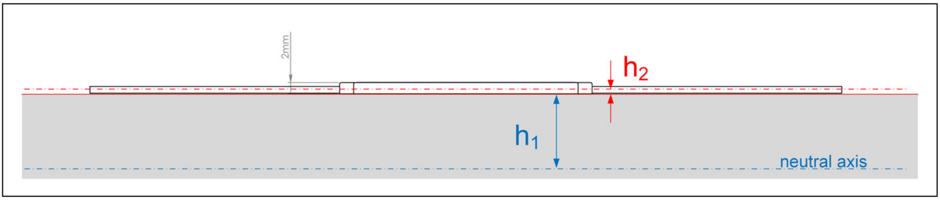

Fig. 3.12 *Distance of the FBG to the mounting surface on the FS62PSS*

However, knowing the distance to the neutral axis (h_1) the measured strain from the sensor can be corrected into strain on the surface by a geometrical factor:

$$\varepsilon_{surface} = \frac{\lambda - \lambda_0}{k \cdot \lambda} \cdot \frac{h_1}{h_2 + h_1} \cdot 10^6$$

Fig. 3.13 *Strain computation bending effect correction*

Where

- $\varepsilon_{surface}$ is the mechanical strain on the measuring surface in µm/m
- λ is the measured Bragg wavelength of the strain sensor in nm
- λ_0 is the Bragg wavelength of the strain sensor at the reference instant in nm
- k is the strain k factor of the strain sensor, dimensionless
- h_1 is the distance from the measuring surface to the neutral axis in mm
- h_2 is the distance from the measuring surface to the FBG in mm (0.25 mm for the FS62PSS and FS62PSR)

Measuring principal stresses

Principal stresses computation with the FS62PSR Patch Strain Rosette can be calculated in accordance to the equation:

$$\sigma_{1/2} = \frac{E}{1-v^2} \cdot \frac{\varepsilon_a + \varepsilon_b + \varepsilon_c}{3} \pm \frac{E}{1+v} \sqrt{\left(\frac{2\varepsilon_a - \varepsilon_b - \varepsilon_c}{3}\right)^2 + \frac{1}{3} \cdot (\varepsilon_b - \varepsilon_c)^2}$$

Where:

- $\sigma_{1/2}$ are the principal stresses, in MPa
- E is the young modulus, in GPa
- v is the Poisson ration, dimensionless
- $\varepsilon_{a/b/c}$ are the the strains measured by the rosette on the three directions, in µm/m

The principal directions are the directions in which the principal normal stresses σ_1 and σ_2 occur as calculated using the equation above. Principal normal stress directions are defined by the angle φ that refers to the rosette's measuring directions, which can be determined using geometrical relationships from the strains ε_a, ε_b and ε_c measured with the rosette.

The aim of the following treatment is to provide the practical engineer with a convenient and reliable method. The theoretical aspects of Mohr's Stress Circle, which forms the basis of this treatment, are described in general literature.

First a tangent of an auxiliary angle ψ is calculated:

$$\tan\psi = \frac{\sqrt{3} \cdot (\varepsilon_b - \varepsilon_c)}{2\varepsilon_a - \varepsilon_b - \varepsilon_c}$$

Considering the signals of the numerator and denominator, the angle φ should be determined using the following scheme:

		Numerator $\sqrt{3} \cdot (\varepsilon_b - \varepsilon_c)$	
		Negative	Positive
Denominator $2\varepsilon_a - \varepsilon_b - \varepsilon_c$	Positive	$\varphi = \frac{1}{2} \cdot (180° - \lvert\psi\rvert)$	$\varphi = \frac{1}{2} \cdot (0° + \lvert\psi\rvert)$
	Negative	$\varphi = \frac{1}{2} \cdot (180° + \lvert\psi\rvert)$	$\varphi = \frac{1}{2} \cdot (360° - \lvert\psi\rvert)$

The angle φ found in this manner should be applied from the axis of the reference measuring position a in the mathematically positive direction (counter-clockwise). The axis of the measuring direction “a” forms one arm of the angle φ. The other arm represents the first principal direction. This is the direction of the principal normal stress σ_1 (identical with the principal strain direction ε_1). The point of the angle is located at the intersection of the axes perpendicular to the measuring directions. The second principal direction (direction of the principal normal stress σ_2) has the angle φ +90°.

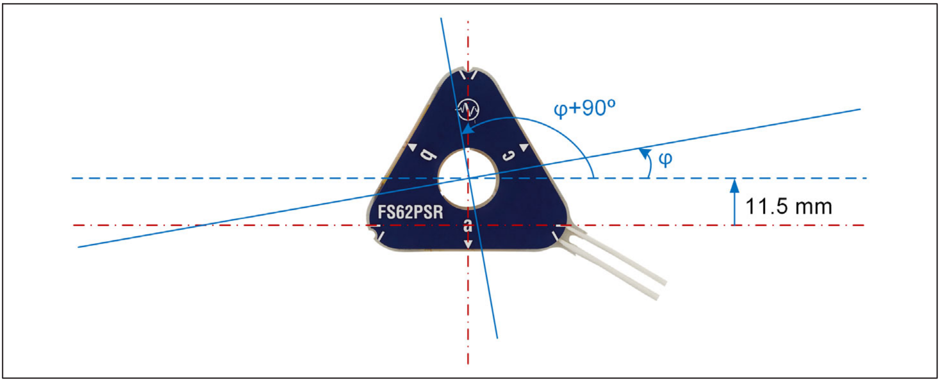

Fig. 3.14 Principal strain directions

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