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Freeze-Warping Box

Measuring the Deflection of a Composite
Specimen

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ABSTRACT

ENGLISH

The topic for this thesis is the performance of the **freeze-warping box.** The freeze-warping box is a device that measures the **bi-material bending** of a composite exposed to a freeze-thaw cycle. The bi-material bending is caused by the thermal mismatch between the different materials in a composite.

Building structures in the real world are made up of composite elements that are exposed to variable temperature and climate conditions. The thermal mismatch between the composite's materials can cause a detrimental **thermal stress** to the structure. The freeze-warping box combined with the **bi-material bending theory** can be used to measure this thermal stress.

A series of tests were performed to check the freeze-warping box's reliability, and to find the relation between the freeze-warping box's equipment's setting and the composite specimen's temperature. A **recommended procedure** for operating the freeze-warping box is included in the thesis.

NORSK

Emnet for denne oppgaven er **freeze-warpingboksen (fryse-nedbøyningsboksen).** Freeze-warpingboksen er et apparat som måler **bøyningen** til en komposittprøve utsatt i en fryse-tiningssyklus. Bøyningen er forårsaket av de ulike termiske egenskapene til de ulike materialene i en kompositt.

Konstruksjoner i den virkelige verdenen er ofte laget av kompositter. Disse komposittene er utsatt for varierende vær og temperatur svingninger. Pga. den manglede termiske samhørigheten mellom materialene i en kompositt, kan det dermed dannes en termisk spenning i kompositten. Spenningen kan virke ugunstig ved at skader kan oppstå. Denne spenningen kan måles ved hjelp av freeze-warpingboksen og **bi-material bøyningsteorien.**

En serie med tester ble utført for å sjekke freeze-warpingboksens pålitelighet og for å finne forholdet mellom freeze-warpingboksens innstillinger og komposittprøvens temperatur. Det er også utviklet en **anbefalt fremgangsmetode** for bruk av freeze-warpingboksen.

ACKNOWLEDGMENTS

ENGLISH

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I wish to express my gratitude for my advisor Stefan Jacobsen, and Andrei Shpak for their continual guidance throughout the making of this thesis. I again would like to thank both Andrei Shpak and Ole Christian Børsum for providing a video demo on how to calibrate the freeze-warping box. Furthermore, I would like to thank the people at the laboratories of *Department of Structural Engineering* (Ove Loraas, Steinar Seehus, Christian Frugone, and Bjørn Stickert Schjølsberg) for providing help and access to the lab, and Alisa Machner for teaching me how to use several of the lab's equipment, and Kjetil Eriksen from the *Department of Geoscience and Petroleum* laboratories for sawing my specimens.

I also wish to thank my mother and brother for their moral support, and my father whom has called me every day to hear how this thesis was progressing.

NORSK

Masteroppgaven i *TKT4920 – prosjektering av konstruksjoner* ble utført ved *institutt for konstruksjonsteknikk, NTNU*.

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Jeg vil også takke min familie for deres støtte.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

The topic for this thesis is the performance of the **freeze-warping box** (see Figure 1.1.-1) The freeze-warping box is used to measure the **bi-material deflection** $\boldsymbol{\delta_{specimen}}$ of a **composite specimen** during a freeze-thaw cycle.

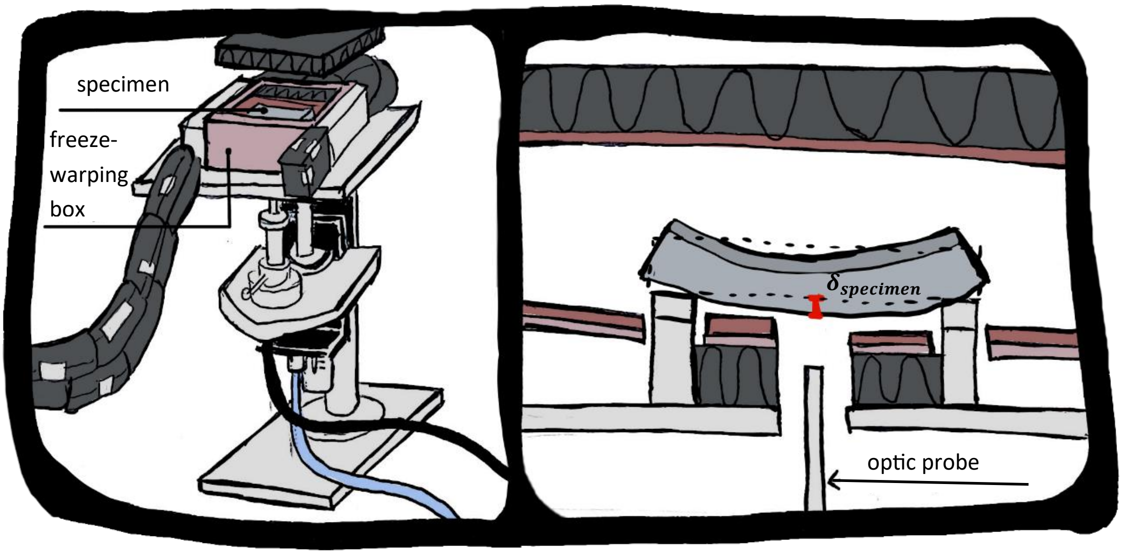


Figure 1.1-1 Composite specimen in the freeze-warping box

A **composite** is an element that is composed of more than one **layer**. Layers may differ by material, water saturation, curing conditions, etc. These layers may have different thermal properties. This thesis will mostly look at concrete composites.

Bi-material deflection $\boldsymbol{\delta_{specimen}}$ is caused by the mismatch between the two materials' thermal properties.

$\delta_{specimen}$ is measured by an **optic probe**. The optic probe emits light to the specimen, and the specimen reflects light back to the optic probe. The amount of reflected light the optic probe receives depends on $\delta_{specimen}$.

In the real world, building structures are made of composite materials and exposed to varying temperature conditions. The composite's layers behave differently under temperature changes. Their thermal mismatch can be detrimental, resulting in stresses in the composite. This stress can be studied applying **bi-material bending theory** by Valenza and Scherer, and by measuring a composite's bi-material deflection in a freeze-warping box. The freeze-warping box is therefore a topic of interest.

1.2 REVIEW

THEORY

Frost damage mechanism [1.1] [1.2] [1.3]

Water and concrete behave differently during freezing. When water freezes to ice, its volume expands. Concrete is a porous material that can be filled with water. When the pore water freezes, its volume expansion can create pressure inside the concrete. If this pressure exceeds the concrete's tensile strength, frost damage occurs.

The freezing-point of pore water is affected by the pore's size. The smaller the pore's size, the lower the freezing-point. This means pore water is very small pores will begin to freeze at temperatures far below 0 [ºC].

Ice in small pores can suck unfrozen water towards itself. This creates a negative pressure in the concrete.

Concrete sustains two main types of frost damages; cracking and scaling.

- **Cracking** is characterized by a permanent volume increase of the concrete material. The damage (cracks) may or may not be visible on the concrete surface.
- **Scaling** is when the concrete's surface gradually crumbles and flakes off.

1.3 SCOPE

The freeze-warping box is an experimental setup developed by Valenza and Scherer [1.4]. The scope for this thesis is to develop a **recommended procedure** for operating the freeze-warping box, with the equipment available at NTNU, and to investigate the accuracy of the freeze-warping box's measurements. The recommended procedure includes:

- An illustrated guide that describes how the freeze-warping box's equipment work. (See chapter 2.1 and 2.2)
- A description of how the bi-material bending $\delta_{specimen}$ is measured. (See chapter 2.3)
- A step-by-step guide, with photos, on how to operate the freeze-warping box. (See Appendix A)

A series of tests were performed to develop the recommended procedure. These tests are divided into 3 phases.

PHASE 1: FINDING THE SETTING FOR THE PELTEIRS AND JULABO

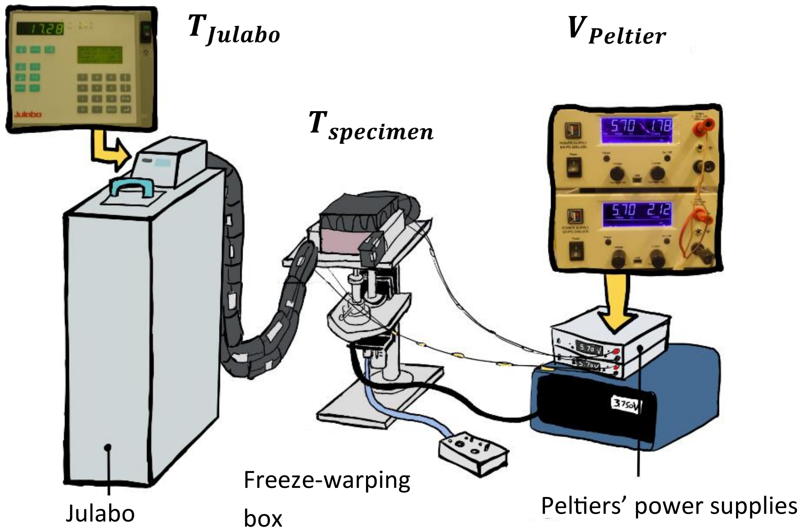


Figure 1.3-1 The equipment that determine the specimen's temperature $T_{specimen}$

The freeze-warping box is attached to several external equipment, as illustrated in Figure 1.3-1. The **specimen's temperature $\boldsymbol{T_{specimen}}$** is primarily determined by these three variables:

1. The setting on the refrigerated/heating circulator (further called **Julabo**), $\boldsymbol{T_{Julabo}}$ [°C]
2. The setting of the **Peltiers**, $\boldsymbol{V_{Peltier}}$ $[V]$
3. The **time $\boldsymbol{\Delta t}$** $[h]$ for $T_{specimen}$ to change after the equipment's setting has been adjusted.

Through trial and error, a series of tests were performed to find the correct equipment settings to obtain the temperatures given below, and the time Δt needed for the temperature to reach equilibrium:

$$T_{specimen} = 20, 10, 0, -10, -20[°C]$$

PHASE 2: DEFORMATION AND DRIFT TESTS

After phase 1, a series of temperature cycle tests were performed to find $\Delta\boldsymbol{\delta}$:

- Temperature cycle 1: $T_{specimen} = 20[°C]$
- Temperature cycle 2: $T_{specimen} = 20, 10, 0, -10, -20, 20[°C]$

Drift and temperature dependent deformation for the freeze-warping box $\Delta\boldsymbol{\delta}$ is caused by the freeze-warping box's equipment, and not the bending of the specimen. $\Delta\boldsymbol{\delta}$ includes drift of the measuring electronics, and the thermal expansion/contraction of the equipment.

An invar steel specimen was used for these tests. The specimen is a homogenous (non-composite) single-phase alloy made up of nickel and iron. It has a much smaller thermal contraction/expansion than steel and concrete. It is therefore not expected to bend during these temperature cycle tests. Any measured “deflection” is considered to be caused by the freeze-warping box’s setup.

Both temperature cycle tests were performed repeatedly to see if the measured $\boldsymbol{\Delta\delta}$ were consistent.

PHASE 3: COMPOSITE TESTS

After phase 2, these following temperature cycles were performed with a steel-mortar composite specimen:

- Temperature cycle 1: $T_{specimen} = 20, 10, 20[°C]$
- Temperature cycle 2: $T_{specimen} = 20, 10, 0, 20[°C]$
- Temperature cycle 3: $T_{specimen} = 20, 10, 0, -10, 20[°C]$
- Temperature cycle 4: $T_{specimen} = 20, 10, 0, -10, -20, 20[°C]$

Phase 3 is based on a previously conducted freeze-warping box experiment by Jacobsen and Scherer [1.3] with steel-mortar composite specimens. The purpose of phase 3 is to control that the developed *recommended procedure* is usable. This is controlled by comparing the composite specimen’s measured bi-material bending with:

- The results in Jacobsen’s and Scherer’s freeze-warping box experiment [1.3]
- Scherer’s and Valenza’s **bi-material bending model** [1.2] (See chapter 2.5)

2 METHODS

2.1 THE FREEZE-WARPING BOX

2.1.1 APPARATUS

FREEZE-WARPING BOX

Freeze-warping box:
- -Freeze-warping box
- -Foam insulation
- -Invar plate with invar supports
- -Copper box with lid

LVDT:
- - LVDT (Linear variable differential transformer)

Optic probe:
- -Fotonic Sensor Signal Amplifier (MTI-2000)
- -Optic probe

Julabo:
- -Refrigerated/heating circulator (Julabo F33)
- -Tubes
- -Water/ethanol mixture

Peltiers:
- -Thermoelectric cooler (TEC)/Peltiers (Marlow Industries inc. DT12-8)
- -Aluminum blocks
- -Thermal contact gel
- -Two power supplies (Power Supply EA-PS 2042-20B)

Measuring equipment:
- -Thermocouples (TC)
- -Quantum X (HBM MXH40B)
- -PC program 'catman®Easy'

Tapes:
- -Butyl tape
- -Duct tape
- -Masking tape

Step motor:
- -Step motor (Oriel Controller model 180008)

SPECIMENS

Composite specimen:

Steel plate:	- 0.5 [mm] thick	
Cement:	- Norwegian OPC (CEM I)	
Aggregate:	- Gneiss-granitic sand according to NS3099, with max diameter = 4 [mm]	
Additives:	- Water-reducer:	Sika polycarboxylate
	- Air entraining admixture:	Sika Aer-S tenside type

Invar steel specimen:
-Invar steel

Dry concrete specimen:
-Any arbitrary mortar mix
-Plastic wrap/thin plastic foil (polyethylene, Toppits GLAD pack)
-Vacuum grease (Super Lube Synthetic grease)

Reflector tab:
-Aluminum foil (Soft Style)
-Vacuum grease (Super Lube Synthetic grease)
-Glue stick

Caliper

2.1.2 SPECIMENS

Dry concrete specimen (phase 1):

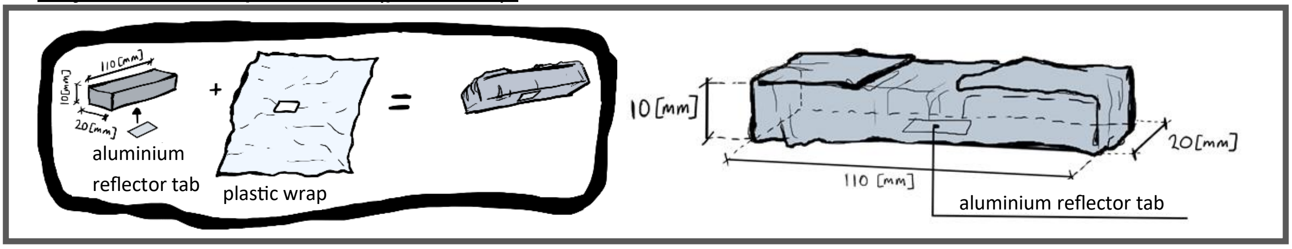


Figure 2.1-1 Dry concrete specimen

The dry concrete specimen has an aluminum foil reflector tab attached underneath it. The reflector is cut into a rectangular shape, and glued onto the specimen with a glue stick. The entire specimen, including the reflector, is covered in a thin layer of vacuum grease and plastic wrap to prevent any moisture exchange with the surroundings.

Dry concrete is a non-composite material. It is not expected to deflect in the freeze-warping box during a freeze-thaw cycle.

Invar steel specimen (phase 1 and 2)

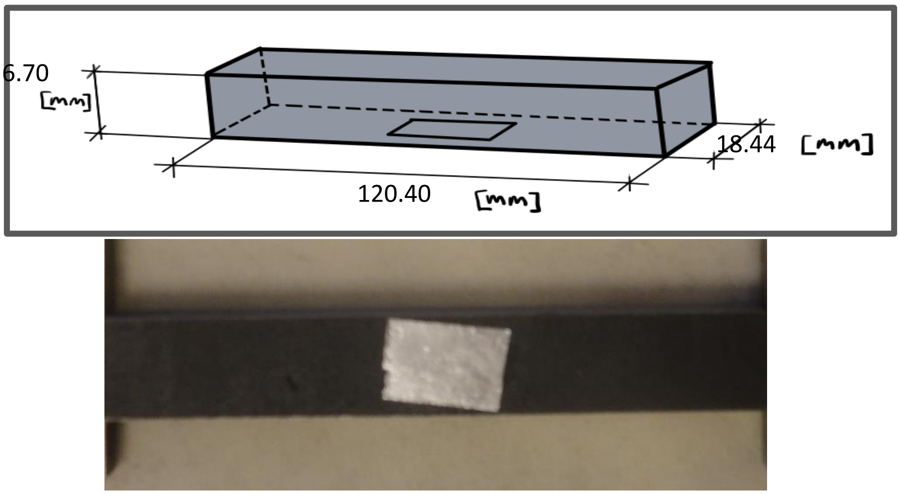


Table 2.1-1 Dimensions of invar steel specimen

Information		
Specimen description	Invar steel	
	Height t_2	0.5
	Width w_2	20
	Length L	92.0
Reflector description	Aluminum foil reflector	
Expected deflection direction	None	

Figure 2.1-2 Invar steel specimen

The invar steel specimen has an aluminum foil reflector tab attached underneath it. The reflector is cut into a rectangular shape, and glued onto the specimen with a glue stick. The reflector tab (only) is covered with vacuum grease to prevent condensation from collecting on it.

Invar steel is a non-composite/homogenous material. It is not expected to deflect in the freeze-warping box during a freeze-thaw cycle.

Composite specimen (phase 1, phase 2 and phase 3)

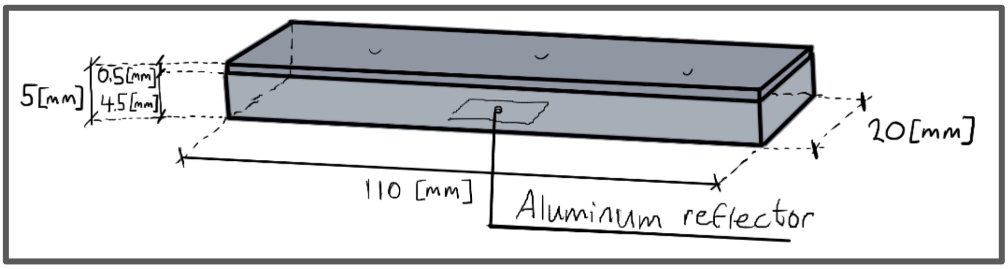


Figure 2.1-3 Targeted dimensions of a steel-concrete composite specimen

h_s = Steel thickness = 0.5 [mm]

h_c =Dry concrete/mortar thickness = 4.5 [mm]

The composite specimen has an aluminum foil reflector tab attached underneath it. The reflector is cut into a rectangular shape, and glued onto the specimen with a glue stick. It is covered with vacuum grease to prevent/reduce condensation from collecting on it.

The composite specimens were prepared and provided by Stefan Jacobsen. The steel plate has anchorage points that are inwardly indented. The dry concrete was cast in steel molds, demolded after 24 hours, then water cured in 28 days, and moist cured with cloth wrapped in plastic for 6-12 months. After curing the specimen was stored in air for approximately 5 years. Finally, it was wet sawn by Kjetil Eriksen with a fine diamond saw into the dimensions given in Figure 2.1-3. The properties of the concrete mixture are shown in Table 2.1-1:

Table 2.1-2 Mortar properties [2.1]

	Unit	
Paste volume fraction (excluding air)	[%]	42.1
Mini-slump *	$[mm]$	87
Mini slump flow diameter*	$[mm]$	132
Fresh density at mixing	$[kg/m^3]$	2005
Air content at mixing	[%]	12.1(+8.1)
Density of specimens after 24 hours demolding	$[kg/m^3]$	2041
Air content of hardened mortar mix	[%]	14.3
Air voids specific surface	$[mm^{-1}]$	20
Spacing factor	$[mm]$	0.21
Water cement ratio	[-]	0.55

* measured with mini cone with height 120 [mm], lower diameter 80 [mm], upper diameter 40 [mm]

The actual specimens that were used are described below:

Due to the difficulties of sawing a specimen with its small dimensions, some of the specimen's mortar sides were uneven. For specimen 1.1 and 2.1, the reflector tab was therefore attached to the specimen's steel side. The deflection results for Specimen 1.1 and 3.1 are not shown in Chapter 3 results. Specimen 1.1 got damaged due to Julabo shutting down, causing the specimen to be exposed to a temperature above 60 [°C]. The results from specimen 3.1 were made during a time when this thesis's writer still lacked practice using the freeze-warping box. The results for specimen 3.1 are therefore moved to Appendix C.

Table 2.1-3 Dimensions of specimen 1.1[3.1]

Information			
Specimen description	Composite beam of steel plate with 0 anchorage points and mortar		
	Steel plate [mm]	Height t_2	0.5
		Width w_2	20
		Length L	92.0
		[N/m²]E-module E_2	$2.1 \cdot 10^{11}$
		[$°C^{-1}$]CTE α_2	0.0000111
	Mortar [mm]	Height t_1	4.5-5.5
		Width w_1	20
		Length L	92.0
		[N/m²]E-module E_1	$2.78 \cdot 10^{8}$
		[$°C^{-1}$]CTE α_1	0.0000075
Reflector description	Aluminum foil reflector glued onto specimen's steel side		
Expected deflection direction	Up		

Figure 2.1-4 Specimen 1.1

Table 2.1-4 Dimensions of specimen 2.1[3.1]

Information			
Specimen description	Composite beam of steel plate with 3 anchorage points and mortar		
	Steel plate [mm]	Height t_1	0.5
		Width w_1	20
		Length L	115
		[N/m²]E-module E_1	$2.1 \cdot 10^{11}$
		[$°C^{-1}$]CTE α_1	0.0000111
	Mortar [mm]	Height t_2	2.5-4.5
		Width w_2	20
		Length L	115
		[N/m²]E-module E_2	$2.78 \cdot 10^{8}$
		[$°C^{-1}$]CTE α_2	0.0000075
Reflector description	Aluminum foil reflector glued onto specimen's steel side		
Expected deflection direction	Up		

Figure 2.1-5 Specimen 2.1

Table 2.1-5 Dimensions of specimen 3.1[3.1]

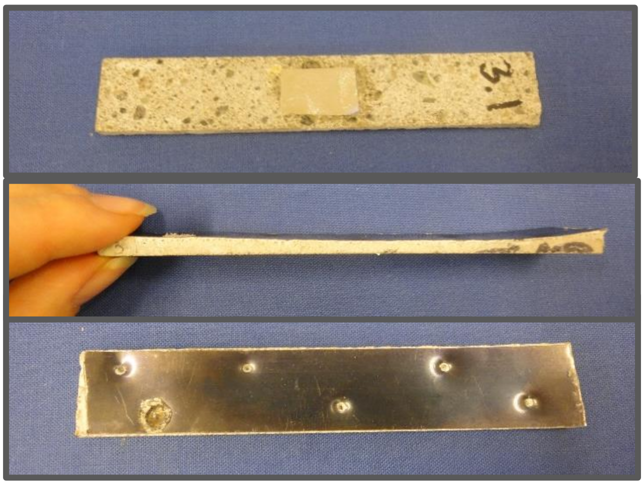


Figure 2.1-6 Specimen 3.1

Information			
Specimen description	Composite beam of steel plate with 6 anchorage points and mortar		
	Steel plate [mm]	Height t_2	0.5
		Width w_2	20
		Length L	94.1
		[N/m²]E-module E_2	2.1·10¹¹
		[°C^{-1}]CTE α_2	0.0000111
	Mortar [mm]	Height t_1	2.5-4.5
		Width w_1	20
		Length L	94.1
		[N/m²]E-module E_1	2.78·10⁸
		[°C^{-1}]CTE α_1	0.0000075
Reflector description	Aluminum foil reflector glued onto specimen's mortar side		
Expected deflection direction	Down		

2.1.3 ABOUT THE FREEZE-WARPING BOX

The freeze-warping box is a laboratory experimental set-up and a test procedure developed by Scherer and Valenza. [2.2] It is used to measure the deflection of a beam specimen exposed to a freeze-thaw cycle. The general set-up of the apparatus is shown below.

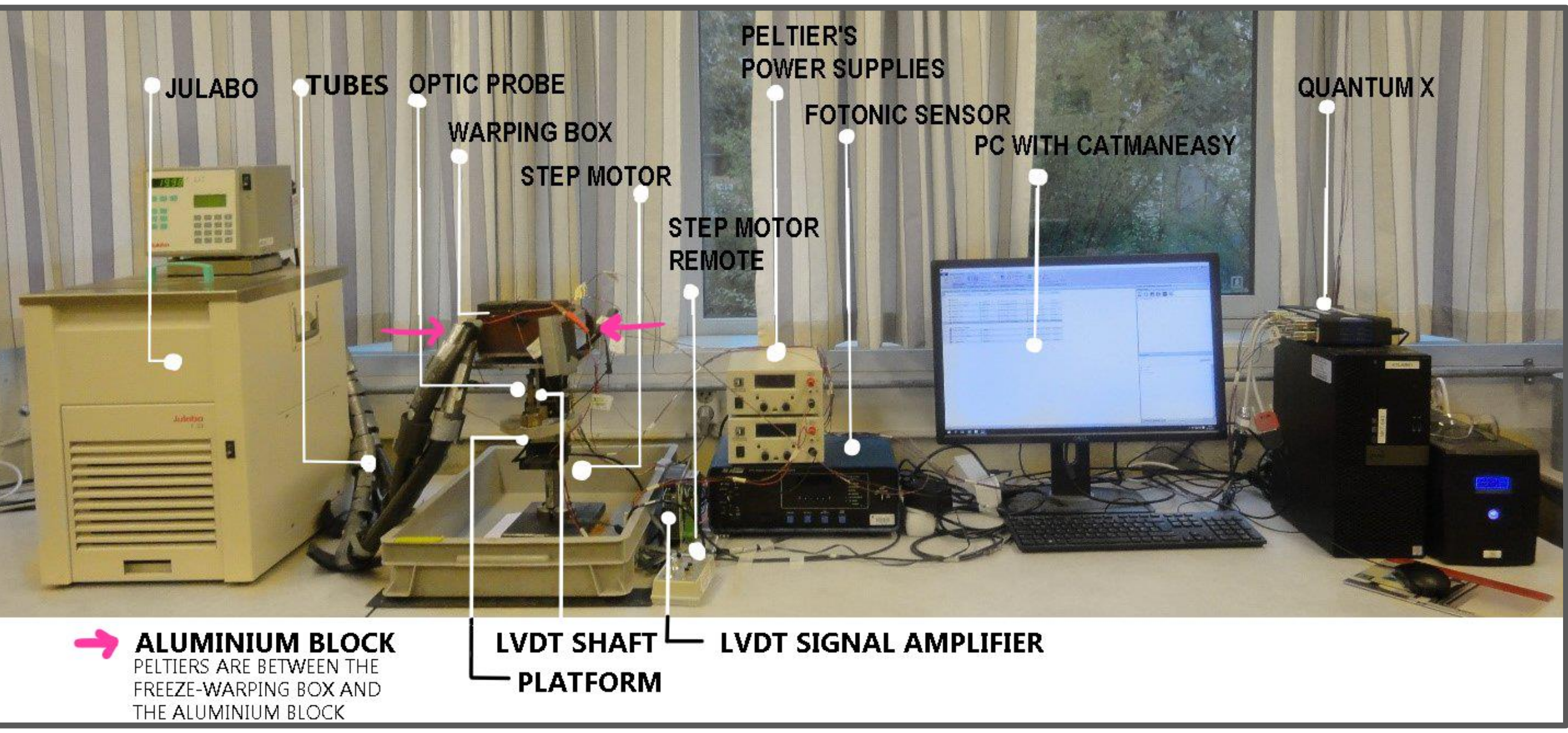
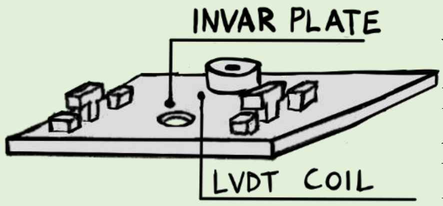
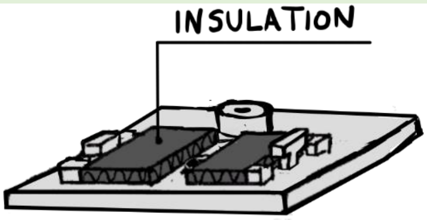


Figure 2.1-7 Setup of the freeze-warping box



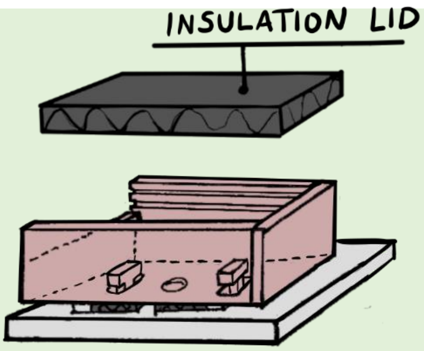
The **invar plate** has four **invar supports for the freeze-warping box**, and two **T-shaped supports for the specimen**. Invar metal has a low thermal conductivity that minimizes the heat loss of the specimen to its surroundings. There is an **LVDT coil** fixed to the invar plate.

Figure 2.1-8 a)



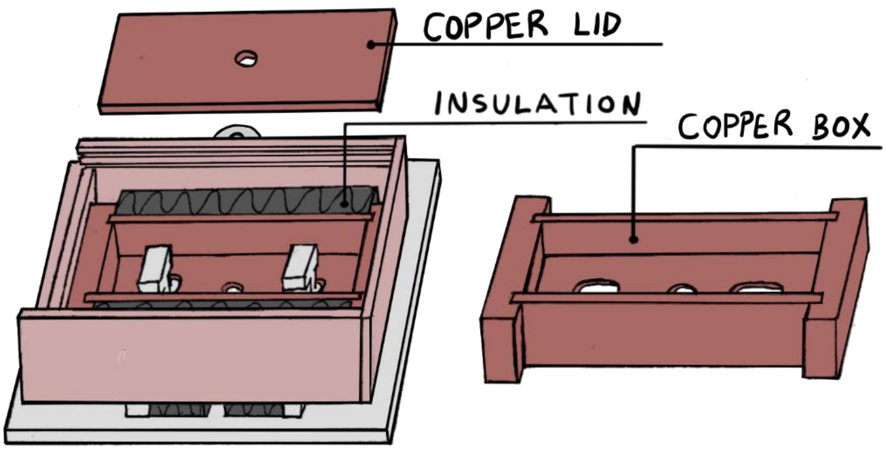
Foam **insulation** is used to insulate the warping box from the invar plate.

Figure 2.1-8 b)



Foam **insulation** is used as a lid. The **freeze-warping box** has **3 holes** at the bottom. The warping box is placed on top of the four invar supports. The T-shaped invar supports protrude the outer holes of the warping box.

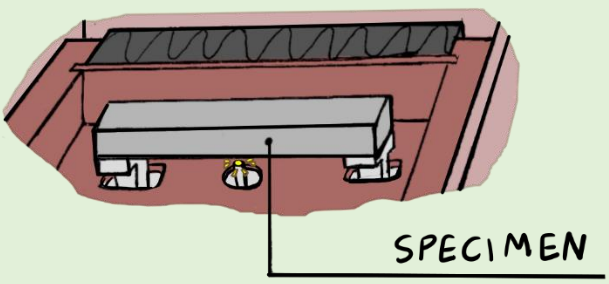
Figure 2.1-8 c)



A **copper box** is placed inside the warping box. The bottom of the box has 3 holes. The T-shaped invar supports protrude through the 2 outer holes of the copper box.

Foam insulation is placed between the warping box and the copper box to prevent heat exchange with surroundings.

Figure 2.1-8 d)



A **specimen** is placed on top of the two T-shaped invar supports. The specimen's reflector tab is facing down.

Figure 2.1-8 e)

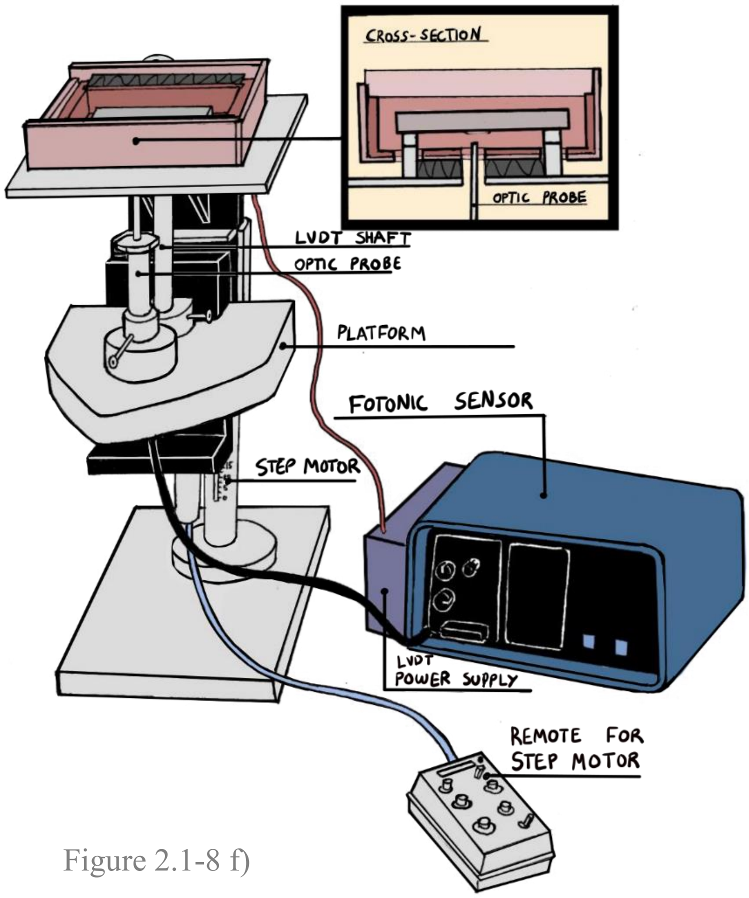


Figure 2.1-8 f)

The invar plate is fixed to a stand. An **optic probe** protrudes the middle hole of the invar plate and the warping box and copper box.

The optic probe and the **LVDT shaft** is on a **platform**. The upper end of the LVDT shaft has a magnetic core that protrudes the LVDT coil.

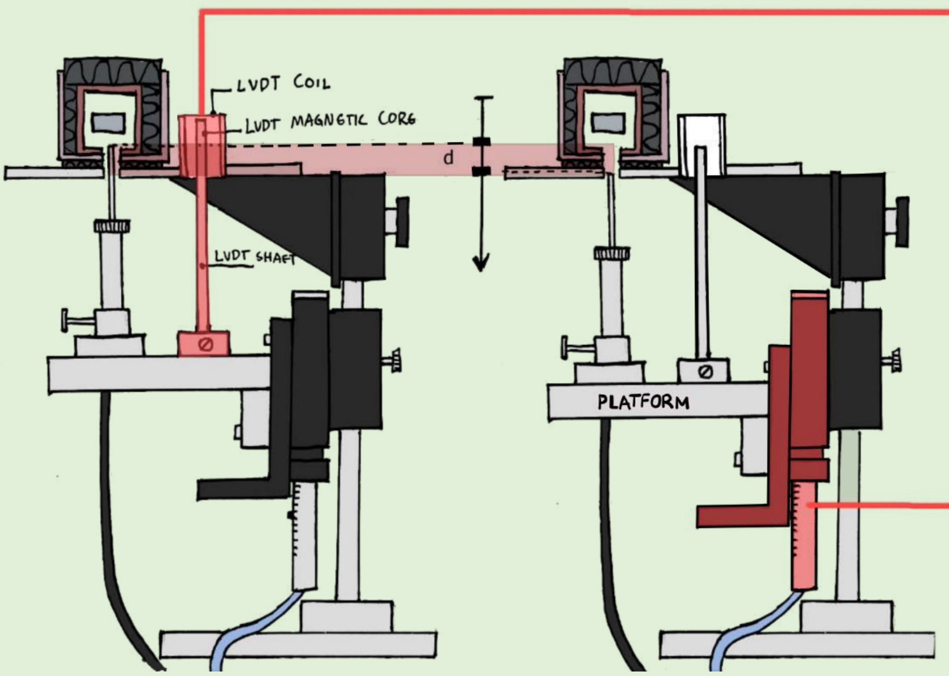


Figure 2.1-8 g)

This is an **LVDT**. It measures the **displacement** $\boldsymbol{d}$ $[\boldsymbol{mm}]$ the step motor positions the optic probe with high precision. It is only used during the **calibration** of the fotonic sensor and the optic probe, and to find the **calibration curve**. (See Chapter 2.2.)

This is a **step-motor**. It lifts the platform (with the optic probe and LVDT) up and down.

NOTICE!

The LVDT does not measure the specimen's deflection δ $[mm]$ during a temperature cycle experiment.

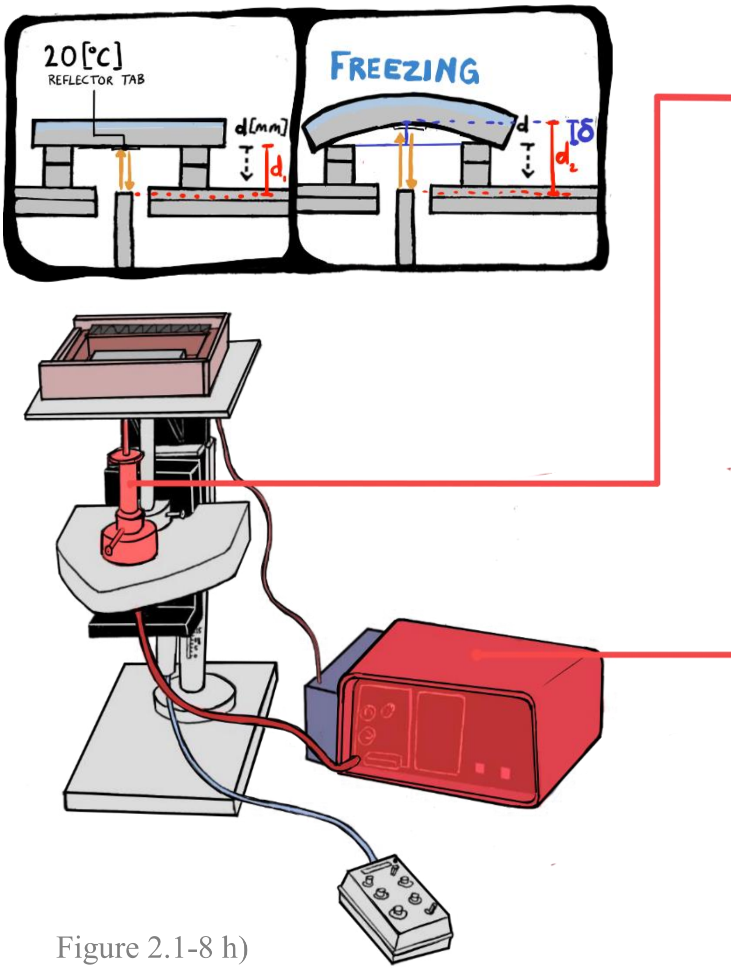


Figure 2.1-8 h)

This is an **optic probe**. It is connected to a fotonic sensor. It is used to measure the specimen's **deflection** $\boldsymbol{\delta[mm]}$ during freezing and thawing. The optic probe emits light to a **reflector tab** attached to the specimen. This light is reflected to the optic probe.

This is a **fotonic sensor signal amplifier** (further called fotonic sensor). It registers the amount of light that is reflected to the optic probe. This reflected light is registered as a voltage $\boldsymbol{I}$ $[\boldsymbol{V}]$**.** The size of I depends on the distance $\boldsymbol{d}$ $[\boldsymbol{mm}]$ between the optic probe's head and the specimen's reflector.

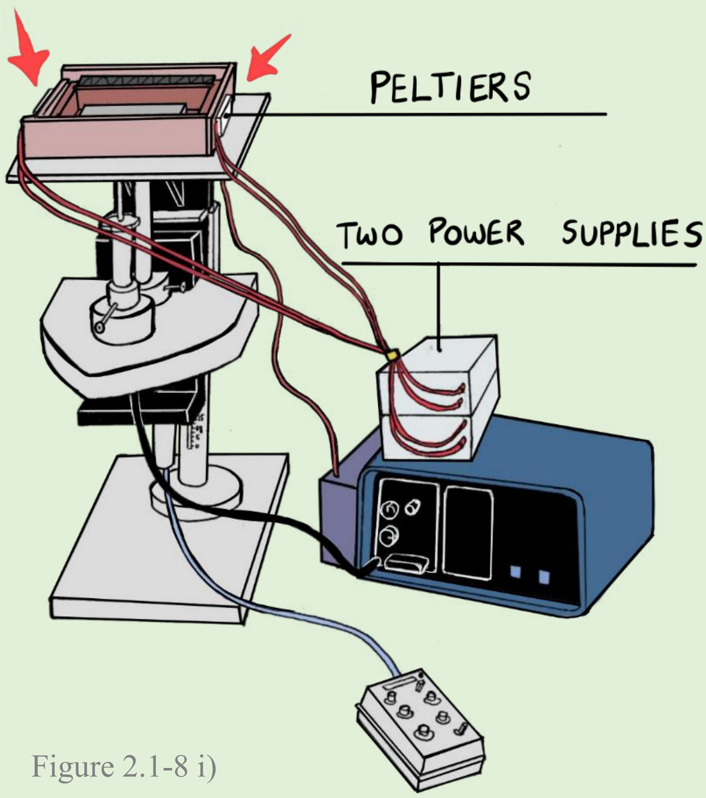


Figure 2.1-8 i)

Two **thermoelectric coolers (TEC/Peltier)** are placed outside the warping box. The Peltiers are used to cool down the warping box.

Thermal contact gel is used between the Peltiers and the freeze-warping box to ensure better heat transfer.

The copper box has a high thermal heat of conductivity which allows the Peltiers to quickly remove heat out of the apparatus.

Each Peltier is connected to its own **power supply.**

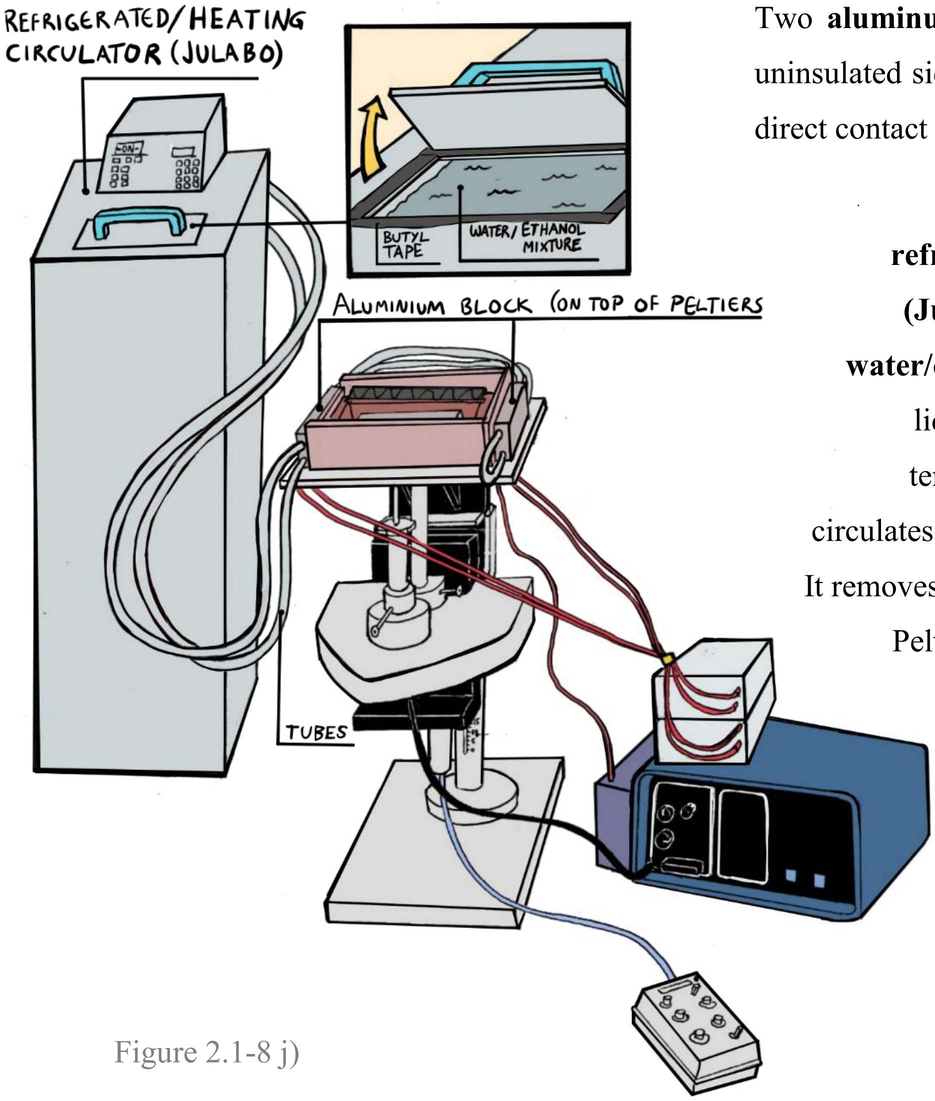


Figure 2.1-8 j)

Two **aluminum blocks** are placed at the uninsulated sides of the warping box, with direct contact with the copper box.

Tubes are connected to a **refrigerated/heating circulator (Julabo)**. Julabo is filled with a **water/ethanol** mixture. Ethanol is a liquid with a very low freezing temperature. Julabo pumps and circulates this liquid through the tubes. It removes heat from the hot side of the Peltiers, and prevents them from overheating.

Butyl tape is taped under Julabo's lid. The tape reduces the amount of ethanol lost to evaporation.

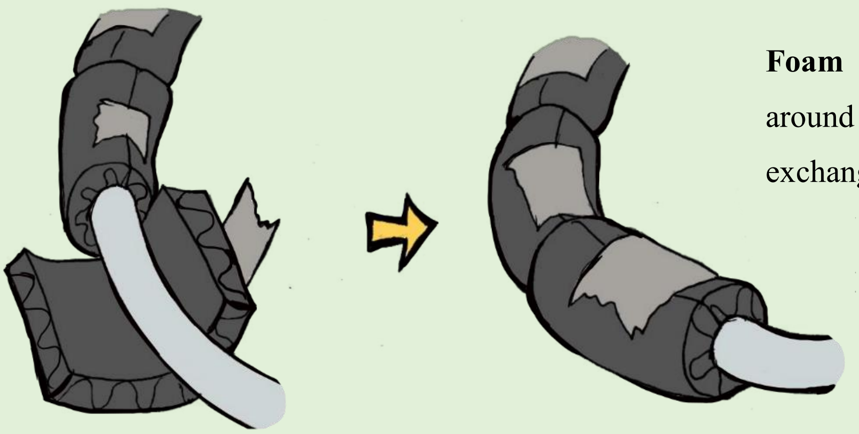


Figure 2.1-8 k)

Foam insulation is duct taped around all the tubes to limit heat exchange with the surroundings.

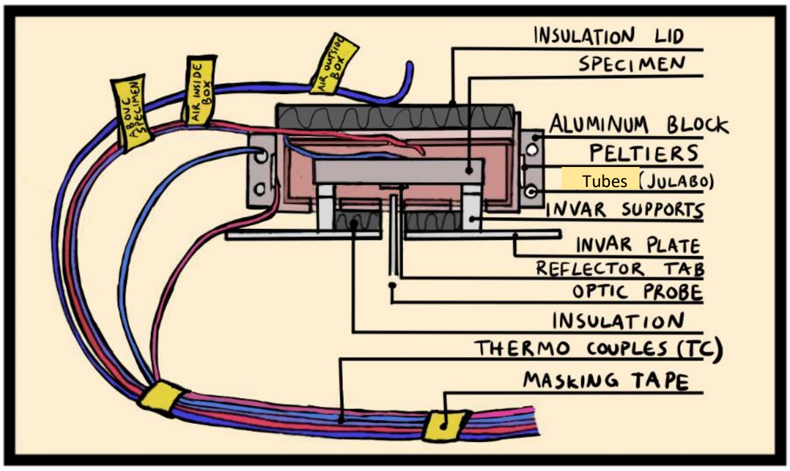


Figure 2.1-8 l)

Five **thermocouples (TC)** are used to monitor the following temperatures:

- inside the copper box, $T_{air,inside}$
- outside the apparatus, $T_{air,outside}$
- above the beam, $T_{specimen,above}$
- cold side of the Peltier, $T_{peltier,cold}$
- (cold) inflowing end of the tube, T_{inlet}

Tape is used to hold the TCs in place.

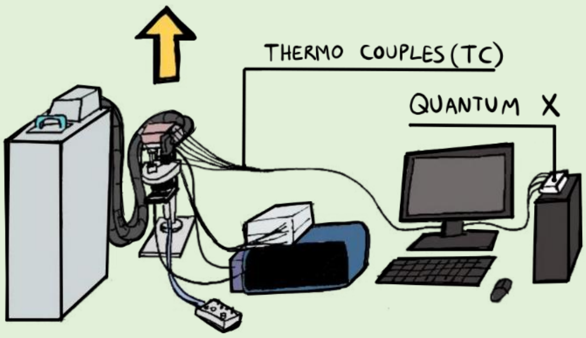
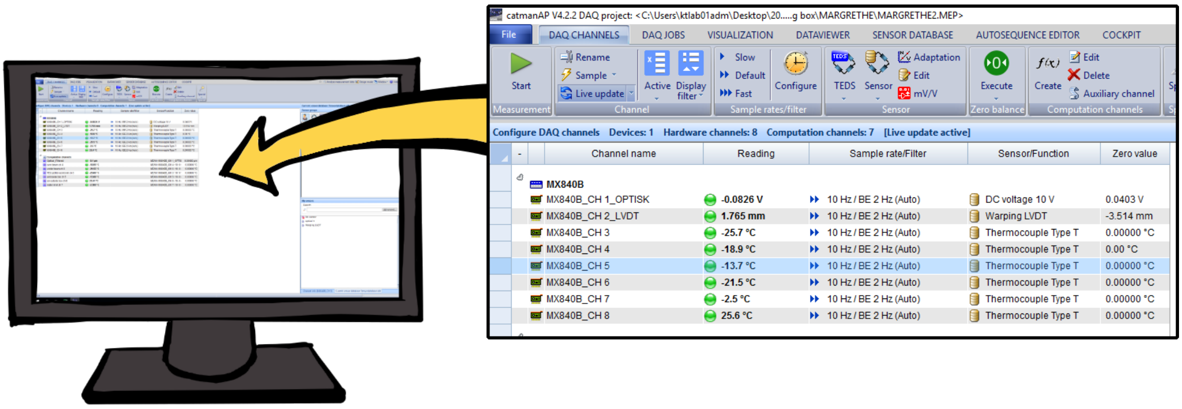


Figure 2.1-8 m)

Quantum X is a device that continuously logs:

- all 5 temperatures measured by the TCs
- the displacement d [mm] measured by the LVDT during the **calibration procedure**.
- the voltage signal I [V] measured by the optic probe.



Channel name	Reading	Sample rate/Filter	Sensor/Function	Zero value
MX840B				
MX840B_CH 1_OPTISK	-0.0826 V	10 Hz / BE 2 Hz (Auto)	DC voltage 10 V	0.0403 V
MX840B_CH 2_LVDT	1.765 mm	10 Hz / BE 2 Hz (Auto)	Warping LVDT	-3.514 mm
MX840B_CH 3	-25.7 °C	10 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 4	-18.9 °C	10 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00 °C
MX840B_CH 5	-13.7 °C	10 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 6	-21.5 °C	10 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 7	-2.5 °C	10 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 8	25.6 °C	10 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C

Figure 2.1-8 n)

This data is transferred from Quantum X to the computer program **catman®Easy**. All the logged measurements can be read in real time.

2.2 CALIBRATION CURVE [2.3]

CALIBRATION PROCEDURE

During the calibration of the fotonic sensor/optic probe, a **calibration curve** is made. It describes the relation between the optic probe's measured reflected light voltage $\boldsymbol{I}$ and the displacement $\boldsymbol{d}$.

During calibration, the LVDT measures the displacement $\boldsymbol{d}$ $[\boldsymbol{mm}]$, and the fotonic sensor/optic probe measures $\boldsymbol{I}[\boldsymbol{V}]$.

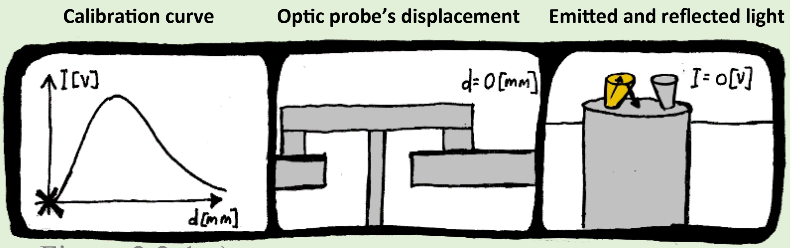


Figure 2.2-1 a)

1. If* the optic probe is in contact with the specimen's reflector, then $I = 0$ $[V]$ and $d = 0$ $[mm]$.

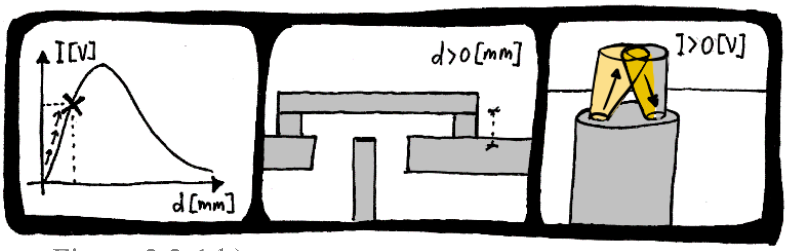


Figure 2.2-1 b)

2. As the optic probe moves away from the specimen, I $[V]$ will gradually increase.

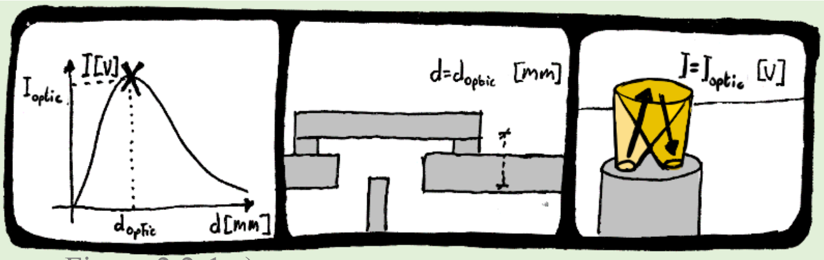


Figure 2.2-1 c)

3. It increases until it reaches an **optic peak,** I_{optic}.

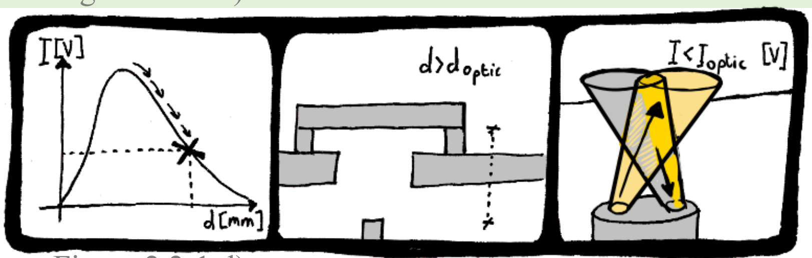


Figure 2.2-1 d)

4. As the optic probe continues to move away from the specimen's surface, I $[V]$ will slowly decrease.

> *NOTICE!
> During the actual calibration procedure, the optic probe must never touch the specimen. There are two reasons for this:
>
> 1. The specimen's reflector is covered in vacuum grease. This can cover the optic probe, and reduce I.
> 2. The optic probe may accidentally move the specimen, and affect the reading for I.

RANGE 1 AND RANGE 2

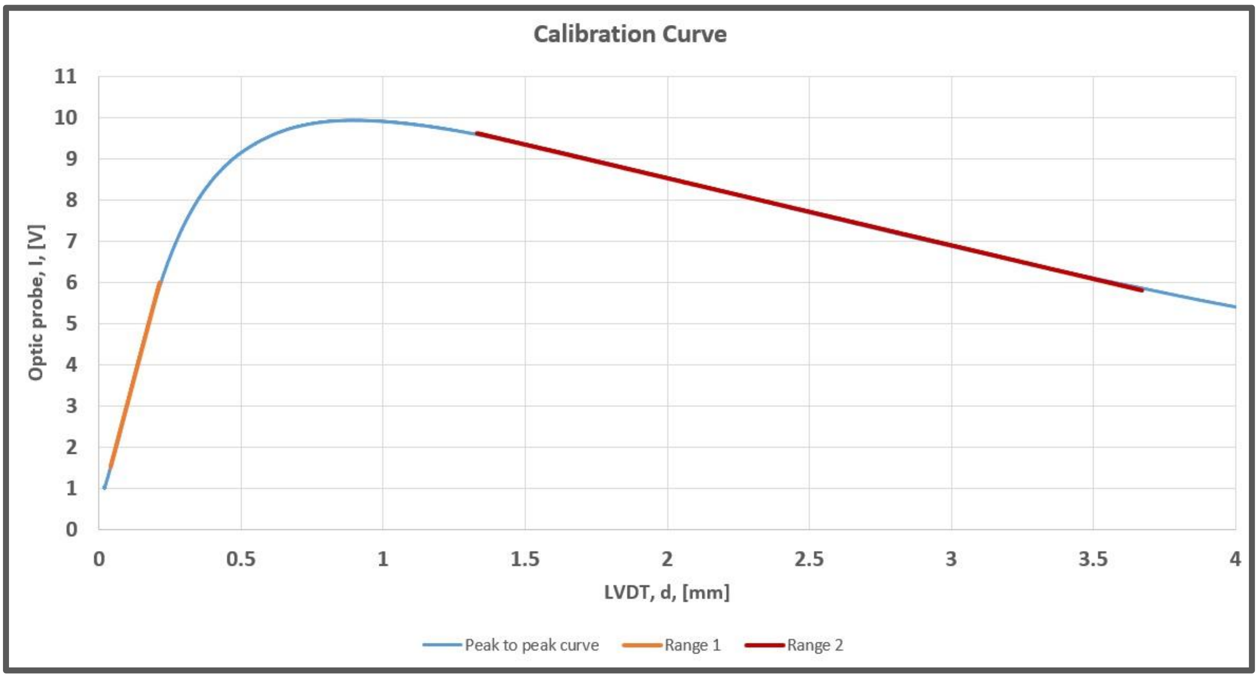


Figure 2.2-2 A typical calibration curve

The calibration curve has two ranges; **Range 1** and **Range 2**. Within these ranges, the calibration curve can be expressed as linear functions:

$$\boxed{\begin{array}{ll} I = md + b & [V] \\ m = \text{slope} & [V/mm] \\ b = \text{intercept} & [V] \end{array}} \tag{2.1}$$

These two ranges allow us to measure the distance d $[mm]$ with great accuracy. Whether Range 1 or Range 2 should be used depends on the size of the deflection δ. In this thesis, Range 1 is used.

Table 2.2-1 Measuring ranges of Range 1 and Range 2.
(These values were found manually.)

	Optic probe, measuring range, I, [V]	**LVDT, measuring range, d, [mm]**	**Deflection measuring range, δ[mm]**	**Start position of the optic probe, δ=0[mm]**	**Linear function [V]**
Range 1	$1.5 < I < 6$	$d < 1$	$\approx \pm 0.1[mm]$	I = 3.750 [V]	$I = m_1 d + b_1$
Range 2	$5.8 < I < 9.62$	$d > 1$	$\approx \pm 1[mm]$	I = 7.710 [V]	$I = m_2 d + b_2$

2.3 CALCULATIONS

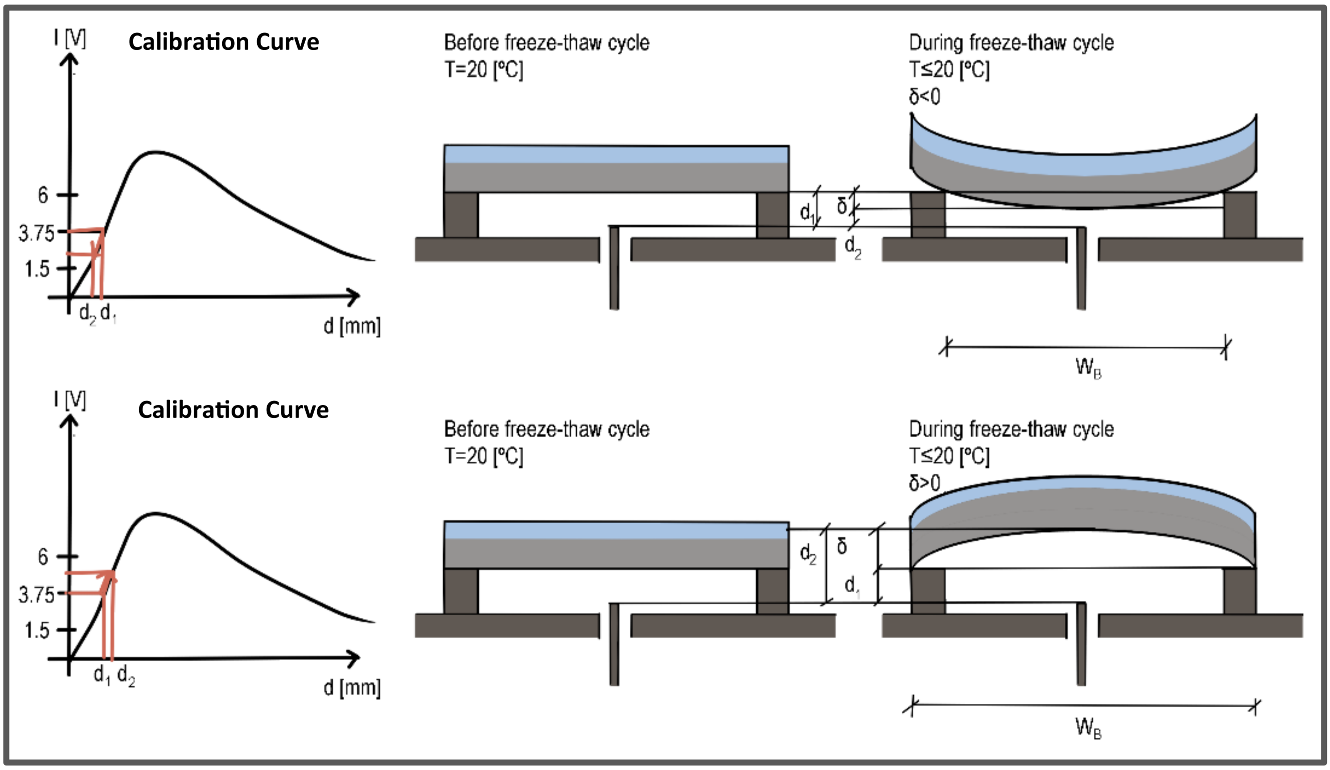


Figure 2.3-1 Optic probe and the calibration curve

Table 2.3-1 Symbol list

Symbols	Definition	Unit
δ	Measured deflection. $\delta = \delta_{specimen} + \Delta\delta = d_2 - d_1$	$[mm]$
$\delta_{specimen}$	Bi-material deflection of the specimen	$[mm]$
$\Delta\delta$	Drift and temperature dependent deformation of the freeze-warping box. $\Delta\delta = \Delta\delta_1 + \Delta\delta_2 + \Delta\delta_3$	$[mm]$
$\Delta\delta_1$	Drift	$[mm]$
$\Delta\delta_2$	Temperature dependent deformation of the freeze-warping box's system	$[mm]$
$\Delta\delta_3$	Condensation	$[mm]$
W_B	Deflection span of the specimen	$[mm]$
d_1	Distance between the specimen and the optic probe, before the freeze-thaw cycle	$[mm]$
d_2	Distance between the specimen and the optic probe, during the freeze-thaw cycle.	$[mm]$
I	The reading of the optic probe	$[V]$
d	Displacement. The distance between the specimen's reflector and the optic probe	$[mm]$
T	Temperature of the specimen	[°C]
t	Time	$[s]$
m_1	Slope of Range 1	$[V/mm]$
b_1	Intercept of Range 1	$[mm]$

MEASURED DEFLECTION δ

1. Before the freeze-thaw cycle, the optic probe is positioned in the middle of Range 1 ($I = 3.750[V]$). The distance between the optic probe and the specimen is measured as:

$$\boxed{d_1 = d(t=0) = \frac{I(t=0)-b_1}{m_1}\ [mm]}\ I = 3.750\ [V], t = 0\ [h] \quad (2.2)$$

2. During the freeze-warping box experiment, the specimen will go through a freeze-thaw cycle. The distance between the specimen and the optic probe is continuously measured as:

$$\boxed{d_2 = d(t) = \frac{I(t)-b_1}{m_1}[mm]} \quad t > 0\ [h] \quad (2.3)$$

The specimen's measured bi-material deflection **δ [mm]** is measured as:

$$\boxed{\delta = d_2 - d_1[\mathrm{mm}]} \quad (2.4)$$

BI-MATERIAL DEFLECTION OF THE SPECIMEN $\delta_{specimen}$

$$\boxed{\delta_{specimen} = \delta - \Delta\delta} \quad (2.5)$$

The **measured deflection, δ** is the deflection that is measured by the optic probe. Parts of this deformation is caused by the freeze-warping box's setup.

The real **deflection of the specimen, $\delta_{specimen}$** is caused by the specimen only.

Δδ is the **drift and temperature dependent deformation** caused by the overall freeze-warping box's setup, and not by the specimen's deflection.

DRIFT AND TEMPERATURE DEPENDENT DEFORMATION $\Delta\delta$

Drift and temperature dependent deformation was measured by running *drift and deformation tests* in phase 2 (See chapters 3.2 and 4.2). $\Delta\delta$ is defined as:

$$\boxed{\Delta\delta = \Delta\delta_1 + \Delta\delta_2 + \Delta\delta_3} \quad (2.6)$$

The **temperature dependent deformation, $\boldsymbol{\Delta\delta_2}$** is caused by the deformation of the overall freeze-warping box's setup during a temperature cycle. It is <u>assumed</u> that the main causes of this deformation are the following:

- Invar supports: a thermal deformation of the invar supports causes a downward "deflection" when the temperature decreases.

- Optic probe: a thermal deformation of the metallic part of the optic probe causes an upward “deflection” when the temperature decreases.

The results of the *freeze-warping box deformation tests* (see chapter 3.2 and 4.2) shows that a temperature decrease in the freeze-warping box consistently results in an “upward” deflection. We therefor assume that the $\Delta\delta_1$ is primarily caused by the deformation of the optic probe.

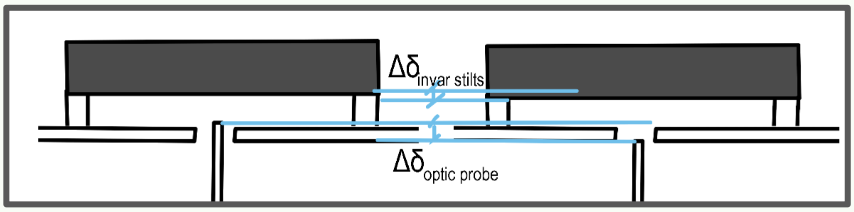


Figure 2.3-2 Temperature dependent deformation $\Delta\delta_1$ caused by the invar supports and the optic probe.

The **drift $\Delta\delta_1$** is caused by the fluctuations of the electronics in the measuring equipment. It is not caused by the temperature deformation of the freeze-warping box’s setup. It is assumed that the fluctuation is caused by the following:

- Measurement uncertainty of the measuring equipment.
- Vibration in the freeze-warping box. It was observed that Julabo and the fotonic sensor causes some vibration. This can be felt by touching the equipment and the table they stand on.

Condensation $\Delta\delta_3$ occurs when the freeze-warping box is below 0[ºC] for an extended time period, and ice begins to collect inside the freeze-warping box. When this ice begins to thaw at T>0[ºC], moisture begins to collect inside the freeze-warping box, and condensation may cover the reflector. This will decrease the measured deflection δ.

Vacuum grease covering the reflector tab is used to minimize $\Delta\delta_3$.

DEFLECTION SPAN W_B

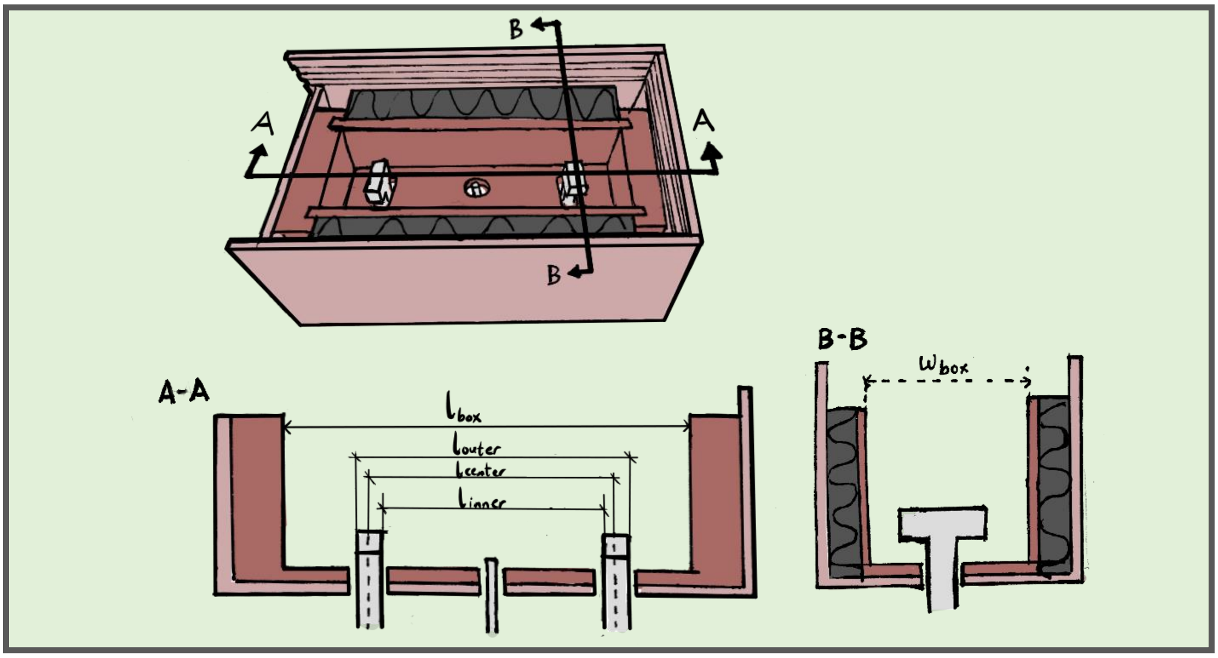


Figure 2.3-3 Freeze-warping box dimensions

Table 2.3-2 Span and deflection

	Span, W_B[mm]	Deflection, δ [mm]
Deflects up	$=\min(l_{outer}, L)$	$\delta > 0$
Deflects down	$= l_{inner}$	$\delta < 0$
Dimensions	**[mm]**	
l_{inner}	94.2	
l_{center}	100.2	
l_{outer}	106.2	
Dimensions	**[cm]**	
l_{box}	≈14	
w_{box}	≈6.9	

From Figure 2.3-1 and Figure 2.3-3, we get the span given in the Table 2.3-2 above.

2.4 PROCEDURE

2.4.1 CALIBRATION PROCEDURE

1. Set up the freeze-warping box equipment as shown in Figure 2.1-7
2. Measure the dimensions of the specimen with a caliper
3. Place the specimen in the freeze-warping box.
4. Calibrate the optic probe/fotonic sensor.

   During calibration, the following measurements should have been logged:

   -The displacement of the LVDT, $d[°C]$

   -The reading of the optic probe, $I[V]$

   Use these measured values to plot the calibration curve. It should look like the figure below:

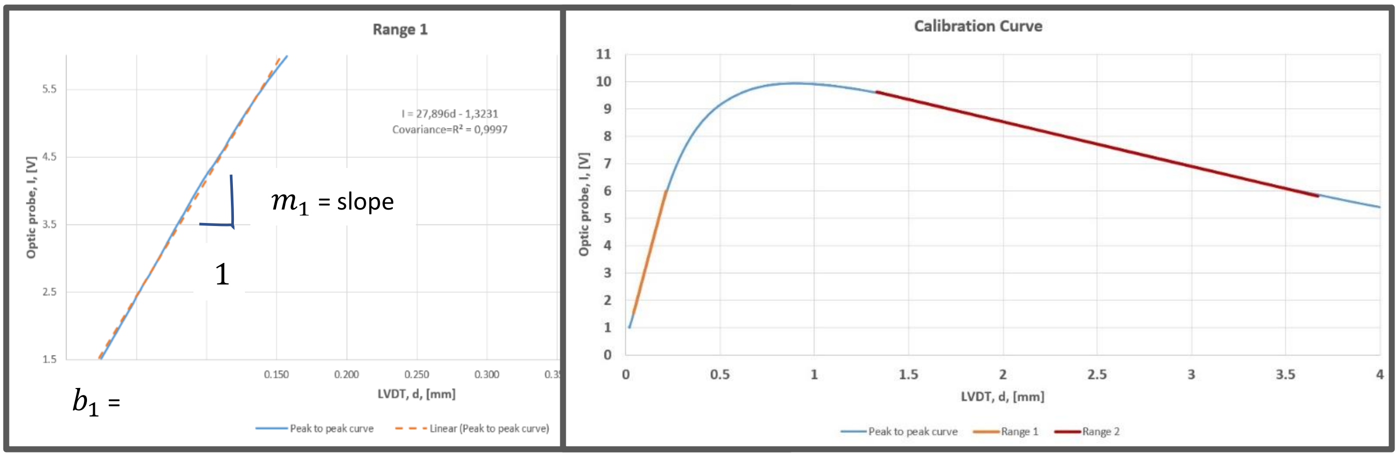


Figure 2.4.1-1 Calibration curve

5. Range 1 is between 1.5 - 6[V]. Make a trendline for Range 1, and express it as a linear function (see equation 2.1):

$$I = m_1 \cdot d + b_1 \ [V]$$

   Depending on which specimen is in the freeze-warping box, continue to either:

   - 2.4.2.1 Phase 1: Finding the setting for the Peltiers and Julabo
   - 2.4.2.2 Phase 2: Deformation and drift tests
   - 2.4.2.3 Phase 3: Composite tests

> *NOTICE!
> The optic probe/fotonic sensor must be re-calibrated whenever:
>
> - A new test is made
> - Whenever the specimen is moved
> - For every new specimen placed in the freeze-warping box

2.4.2 FREEZE-WARPING BOX EXPERIMENT

2.4.2.1 PHASE 1: FINDING THE SETTING FOR THE PELTIERS AND JULABO

Refer to Appendix A.

2.4.2.2 PHASE 2: DEFORMATION AND DRIFT TESTS

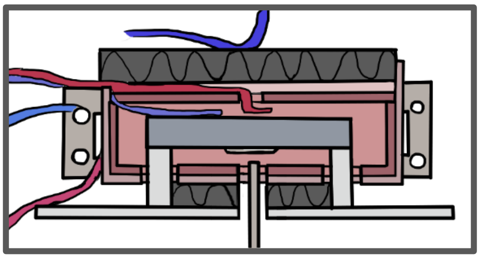


Figure 2.4.2.2-1 Invar steel specimen in freeze-warping box

The invar steel specimen is a homogenous. It is therefore not expected to deflect during a temperature cycle. Any measured "deflection" is therefore assumed to be caused by the deformation and drift of the freeze-warping box.

1. After the calibration procedure, put the specimen through the following two temperature cycles. Re-calibrate the optic probe/fotonic sensor for each temperature cycle.

Table 2.4.2.2-1 *Temperature cycle 1:* finding the temperature dependent deformation $\Delta\delta_1$ and condensation $\Delta\delta_3$

Target temperature in freeze-warping box [°C]	**Accumulated time, t, [h]**	**Time, Δt,[h]**	**Julabo, T_{Julabo} [°C]**	**Peltier, $V_{Peltier}$,[V]**	**Description of temperature change**
20	00:00	01:00	45.8	5.70	Constant
10	01:00	00:30	32.5	5.70	Decrease
10	01:30	02:30	32.5	5.70	Constant
0	04:00	00:30	15.7	5.70	Decrease
0	04:30	02:30	15.7	5.70	Constant
-10	07:00	00:30	2	5.70	Decrease
-10	07:30	02:30	2	5.70	Constant
-20	10:00	00:30	-13	5.70	Decrease
-20	10:30	02:30	-13	5.70	Constant
20	13:00	02:00	45.8	5.70	Increase
20	15:00	03:00	45.8	5.70	Constant

Table 2.4.2.2-2 *Temperature cycle 2*: finding the drift $\Delta\delta_2$

Target temperature in freeze-warping box [°C]	**Accumulated time, t, [h]**	**Time, Δt,[h]**	**Julabo, T_{Julabo} [°C]**	**Peltier, $V_{Peltier}$,[V]**	**Description of temperature change**
20	00:00	01:00	20	0.35	Constant

2. During each temperature cycle, the following should have been measured and logged:

   -The temperature of the specimen, $T_{specimen,above}$[°C]
   -The reading of the optic probe, $I[V]$
   -Time, $t[s]$

   Use equations (2.2), (2.3), and (2.4) and calculate the following values for the freeze-thaw cycle 1:

$$\Delta\delta(t) = d_2(t) - d_1$$

$$d_1 = \frac{I - b_1}{m_1}, \qquad I = 3.750\ [V],\ t = 0[h]$$

$$d_2(t) = \frac{I - b_1}{m_1}, \qquad t > 0[h]$$

3. Plot the following two graphs for temperature cycle 1 and temperature cycle 2:
   - Time-Deflection and Time-Temperature curve
   - Deflection-Temperature

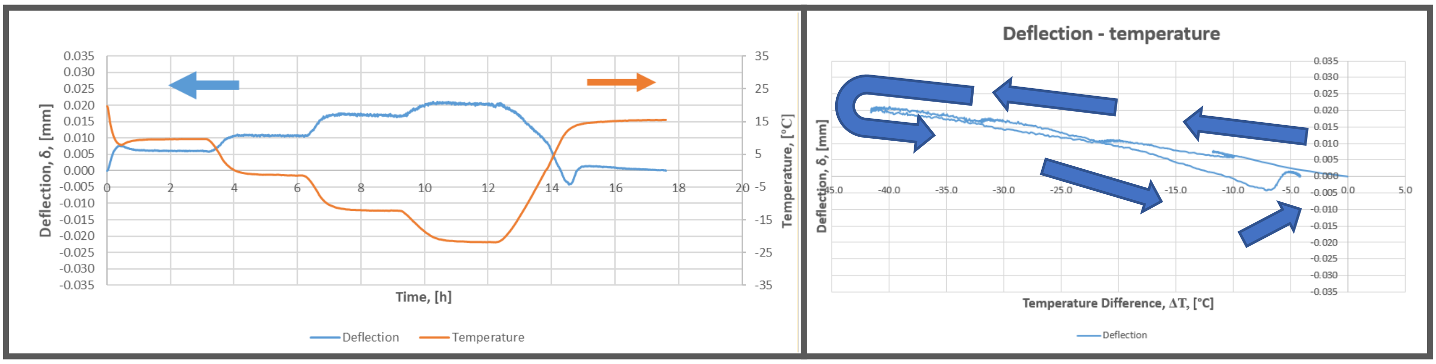


Figure 2.4.2.2-2 Time-Deflection and Time-Temperature (right), and Deflection- Temperature graphs (left) for *temperature cycle 1*

For *temperature cycle 1*, notice how the relation between $\boldsymbol{\Delta\delta_1}$ and the specimen's temperature difference ΔT is close to linear. Make a trendline, and express this relation as a linear function:

$$\boxed{\Delta\delta_1(\Delta T) = m_T \Delta T + b_T,} \quad \text{t < before ice melts} \qquad (2.7)$$

For *temperature cycle 1,* the dip in the Deflection-Temperature curve and the Temperature-Time curve after 14 [h] is caused by condensation $\boldsymbol{\Delta\delta_3}$.

2.4.2.3 PHASE 3: COMPOSITE TESTS

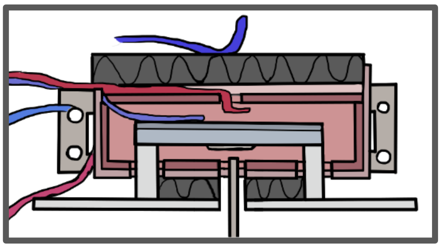


Figure 2.4.2.3-1 Steel-concrete composite specimen in freeze-warping box

The composite test is based on S. Jacobsen and G. Scherer's experiment [2.1]. Their paper is used as a comparison to the results found in this thesis.

1. After the calibration procedure, put the specimen through the following four temperature cycles. Redo the calibration procedure for each temperature cycle.

Table 2.4.2.3-1 Temperature cycle 1: from +20[ºC] to +10[ºC]

Target temperature in freeze-warping box $T_{Specimen,target}$ [°C]	Accumulated time, t, [h]	Time, Δt,[h]	Julabo, T_{Julabo} [°C]	Peltier, $V_{Peltier}$,[V]	Description of temperature change
20	01:00	01:00	45.8	5.70	Constant
10	01:30	00:30	32.5	5.70	Decrease
10	04:00	02:30	32.5	5.70	Constant
20	04:30	00:30	45.8	5.70	Increase
20	07:30+	03:00 +	45.8	5.70	Constant

Table 2.4.2.3-2 Temperature cycle 2: from +20[ºC] to 0[ºC]

Target temperature in freeze-warping box $T_{Specimen,target}$ [°C]	Accumulated time, t, [h]	Time, Δt,[h]	Julabo, T_{Julabo} [°C]	Peltier, $V_{Peltier}$,[V]	Description of temperature change
20	01:00	01:00	45.8	5.70	Constant
10	01:30	00:30	32.5	5.70	Decrease
10	04:00	02:30	32.5	5.70	Constant
0	04:30	00:30	15.7	5.70	Decrease
0	07:00	02:30	15.7	5.70	Constant
20	08:00	01:00	45.8	5.70	Increase
20	11:00+	03:00 +	45.8	5.70	Constant

Table 2.4.2.3-3 Temperature cycle 3: from +20[ºC] to -10[ºC]

Target temperature in freeze-warping box $T_{Specimen,target}$ [°C]	Accumulated time, t, [h]	Time, Δt,[h]	Julabo, T_{Julabo} [°C]	Peltier, $V_{Peltier}$,[V]	Description of temperature change
20	01:00	01:00	45.8	5.70	Constant
10	01:30	00:30	32.5	5.70	Decrease
10	04:00	02:30	32.5	5.70	Constant
0	04:30	00:30	15.7	5.70	Decrease
0	07:00	02:30	15.7	5.70	Constant
-10	07:30	00:30	2	5.70	Decrease
-10	10:00	02:30	2	5.70	Constant
20	11:30	02:00	45.8	5.70	Increase
20	14:30+	03:00+	45.8	5.70	Constant

Table 2.4.2.3-4 Temperature cycle 4: from +20[ºC] to -20[ºC]

Target temperature in freeze-warping box $T_{Specimen,target}$ [°C]	Accumulated time, t, [h]	Time, Δt,[h]	Julabo, T_{Julabo} [°C]	Peltier, $V_{Peltier}$,[V]	Description of temperature change
20	00:00	01:00	45.8	5.70	Constant
10	01:00	00:30	32.5	5.70	Decrease
10	01:30	02:30	32.5	5.70	Constant
0	04:00	00:30	15.7	5.70	Decrease
0	04:30	02:30	15.7	5.70	Constant
-10	07:00	00:30	2	5.70	Decrease
-10	07:30	02:30	2	5.70	Constant
-20	10:00	00:30	-13	5.70	Decrease
-20	10:30	02:30	-13	5.70	Constant
20	13:00	02:00	45.8	5.70	Increase
20	15:00	03:00	45.8	5.70	Constant

2. Take off the lid on the freeze-warping box, and carefully remove the sample. Inspect it for any possible frost damage.
3. During the temperature cycles, the following should have been measured and logged:

   -The temperature of the specimen, T[°C]
   -The reading of the optic probe, $I[V]$
   -Time, $t[s]$

   Use equations (2.6) and (2.7) and calculate the following values for each temperature cycle:

$$\delta_{specimen}(t) = d_2(t) - d_1 - \Delta\delta(\Delta T(t))$$

$$d_1 = \frac{I-b_1}{m_1}, \qquad I = 3.750\,[V], t = 0[h]$$

$$d_2(t) = \frac{I-b_1}{m_1}, \qquad t > 0[h]$$

4. Plot the two following graphs (like Figure 2.4.2.2-2) for all four temperature cycles:
   - Time-Deflection curve, and Time-Temperature curve
   - Temperature-deflection curve for all freeze-thaw

2.5 MODELING, TIMOSHENKO-SCHERER/VALENZA [2.2]

Table 2.5-1 Symbol list

Symbols	Definition	Unit
$\delta_{specimen}$	Bi-material deflection of the specimen	$[mm]$
W_B	Deflection span of the specimen	$[mm]$
w_1	Width of material 1	$[mm]$
w_2	Width of material 2	$[mm]$
K_R	Curvature	$[mm^{-1}]$
$\Delta\varepsilon_f$	Strain between the two material surfaces	$[-]$
d	Distance between the specimen and the optic probe, OR the displacement of the platform/optic probe/ LVDT during calibration.	$[mm]$
$T_{specimen,1}$	The specimen's temperature before a temperature cycle	$[°C]$
$T_{specimen,2}$	The specimen's lowest temperature during a temperature cycle	$[°C]$
E_1	Elastic modulus of material 1	$[Nmm^{-2}]$
E_2	Elastic modulus of material 2	$[Nmm^{-2}]$
α_1	Coefficient of thermal expansion (CTE) of material 1	$[°C^{-1}]$
α_2	Coefficient of thermal expansion (CTE) of material 1	$[°C^{-1}]$

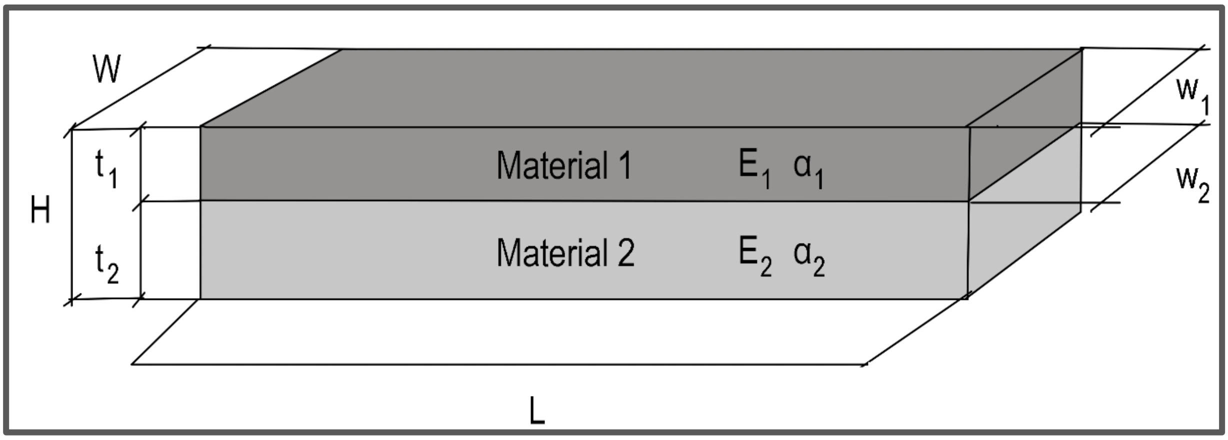


Figure 2.5-1 Bi-material specimen

Scherer and Valenza's **bi-material bending model** describes the specimen's deflection $\delta_{specimen}$ during a freeze-thaw cycle. The model is based on Timoshenko's beam theory. Their model assumes that the composite beam behaves elastically (no permanent deformation).

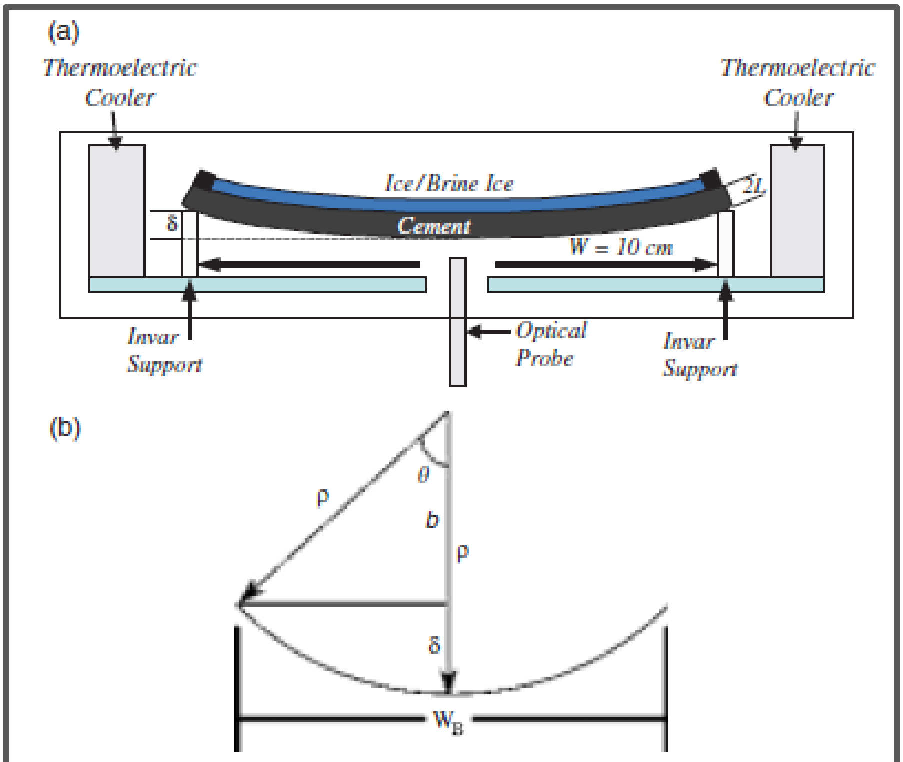


Fig. 14. (a) Schematic of the warping experiment. The experiment consists of simply supporting a thin plate of cement paste, confining a pool of fluid to the surface of the plate, and exposing the system to a temperature cycle. (b) Geometrical representation of bi-material bending.

Figure 2.5-2 Bi-material deflection. (Taken from Scherer and Valenza's PhD thesis that focuses on a composite of concrete and salt solution/ice) [2.2]

The model states that the deflection of a composite beam follows this equation:

$$\boxed{\delta_{specimen} = \frac{W_B}{8\rho}} \tag{2.8}$$

From Table 2.3-2 we know the specimen's deflection span W_B. $\frac{1}{\rho}$ is a constant that is given by the following formula:

$$\boxed{\frac{1}{\rho} = \frac{\Delta\varepsilon_f K_R}{H}} \tag{2.9}$$

Where:

$$K_R = \frac{6(1+m^2)mnl}{1+4mnl+l^2m^4n^2+6m^2nl+4m^3nl}, \qquad \mathrm{H} = h_1 + h_2, \quad m = \frac{t_1}{t_2}, \ n = \frac{E_1}{E_2}, \ l = \frac{w_1}{w_2},$$

$$\Delta\varepsilon_f = \Delta\alpha\Delta T \,, \qquad \Delta\alpha = \alpha_1 - \alpha_2, \Delta T = T_{specimen,2} - T_{specimen1},$$

Notice that the materials' CTE ($\alpha_1$and α_2) and the specimen's temperature ΔT determines if the specimen deflects up or down.

The measured deflection found in 3 Results will be compared to the equation (2.8)

3 RESULTS

3.1 PHASE 1: FINDING THE SETTING FOR THE PELTIERS AND JULABO

For all the results found through trial and error, refer to Appendix B.1.

3.1.1 SPECIMEN'S TEMPERATURE $T_{specimen,above}$ VS. PELTIERS' VOLTAGE $V_{Peltier}$

The graph below describes the relation between the specimen's temperature $T_{specimen,above}$ (measured by the TC) and the Peltiers' voltage setting $V_{Peltier}$. The graph is based on the results from *Peltier Experiment test 5* (see Appendix B.1.2).

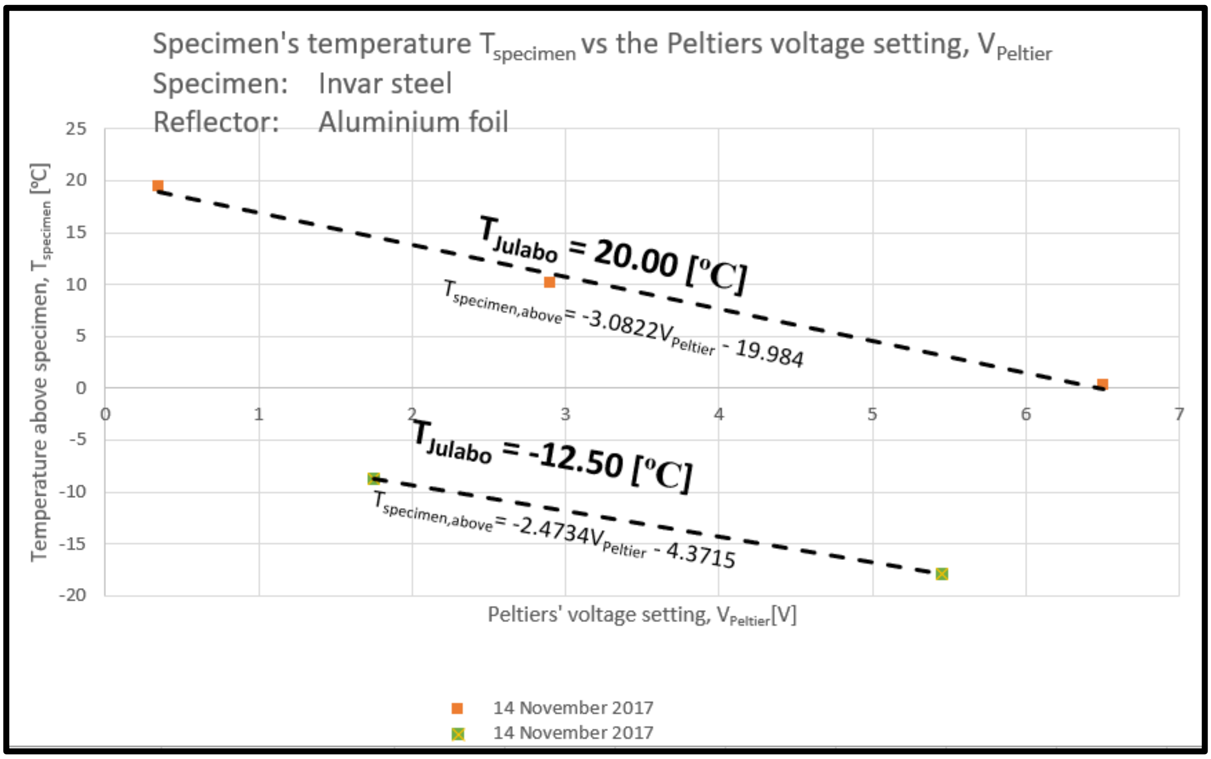


Figure 3.1.1-1 Trendline showing relation between $T_{specimen,above}$ and $V_{Peltier}$

Table 3.1.1-1 Measured $T_{specimen,above}$ and $V_{Peltier}$

Julabo = 20 [°c]	**Time [h]**	0	1	1	
	Peltiers [V]	0.35	1.45	2.9	
Peltier Experiment test 5 **14 November**	**REAL temperature, over beam, $T_{specimen,above}$ [°C]**	19.4	10.2	0.3	
Julabo = -12.5 [°c]	**Time [h]**	1	1	1	1
	Peltiers [V]	0.6	1.75	3.5	5.45
Peltier Experiment test 5 **14 November**	**REAL temperature, over beam, $T_{specimen,above}$ [°C]**	-4.4	-9.1	-13.3	-18.7

3.1.2 SPECIMEN'S TEMPERATURE $T_{specimen}$ VS. JULABO's TEMPERATURE T_{Julabo}

The graph below describes the relation between the specimen's temperature $T_{specimen,above}$ (measured by the TC) and Jualbo's temperature setting T_{Julabo} . The graph is based on the results from *Julabo Experiment tests 3, 4, 5, and 6* (see Appendix B.1.3 or chapter 3.2.1). Julabo's temperature has a lower limit of $\boldsymbol{T_{Julabo}}$**<22[ºC].**

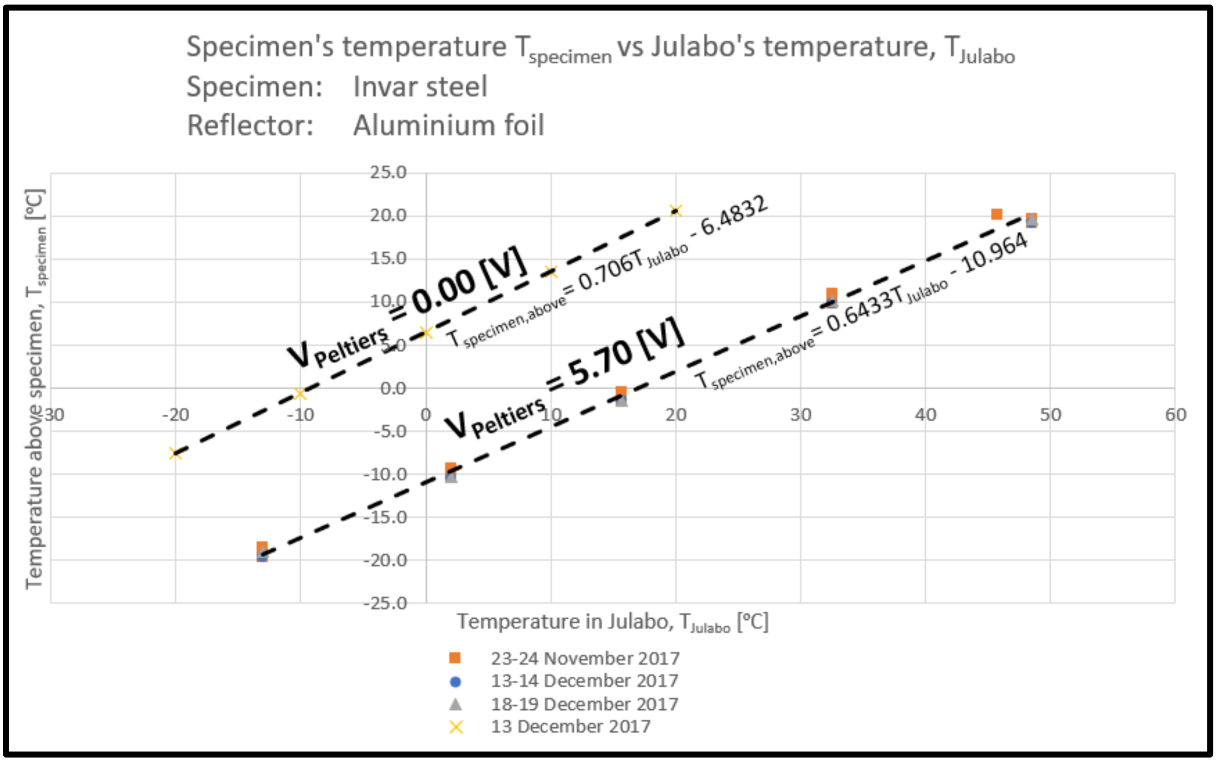


Figure 3.1.2-1 Trendline showing relation between $T_{specimen,above}$ and T_{Julabo}

Table 3.1.2-1 Measured $T_{specimen,above}$ and T_{Julabo}

Peltiers = 5.70 [V]	**Time [h]**	1	3	3	3	3
	Julabo [°C]	45.8	32.5	15.7	2	-13
Julabo Experiment tests 3 **23-24 November**	**REAL temperature, over beam, $T_{specimen,above}$ [°C]**	20.1	10.9	-0.4	-9.3	-18.5
Julabo Experiment test 4s *6***13-14 December**	**REAL temperature, over beam, $T_{specimen,above}$ [°C]**	19.2	9.9	-1.5	-10.5	-19.6
Julabo Experiment test 5: *6***18-19 December**	**REAL temperature, over beam, $T_{specimen,above}$ [°C]**	19.6	10.1	-1.4	-10.3	-19.1
Peltiers = 0.00 [V]	**Time [h]**	1	3	3	3	3
	Julabo [°C]	20	10	0	-10	-20
Julabo Experiment test 67s **13-14 December**	**REAL temperature, over beam, $T_{specimen,above}$ [°C]**	20.7	13.5	6.4	-0.6	-7.6

3.2 PHASE 2: DEFORMATION AND DRIFT TESTS

3.2.1 TEMPERATURE DEPENDENT DEFORMATION $\Delta\delta_1$ AND CONDENSATION $\Delta\delta_3$

TEMPERATURE CYCLE 1-TEST 1

Table 3.2.1-1

TEMPERATURE CYCLE 1-TEST 1 23 November 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil reflector and vacuum grease						
Time, t [h]	1	3	3	3	3	5+
REAL temperature, over beam, $T_{specimen,above}$ [°C]	20.1	10.9	-0.4	-9.3	-18.5	19.6
$\Delta\delta_1 + \Delta\delta_3$ [μm]	0.5	6.9	14.9	21.7	29.0	0.4

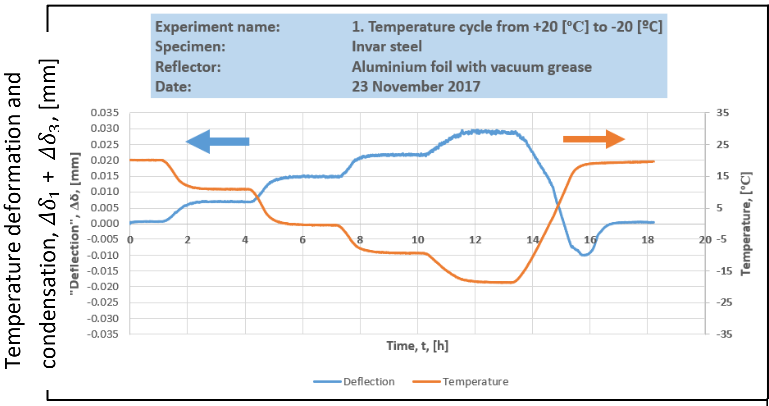
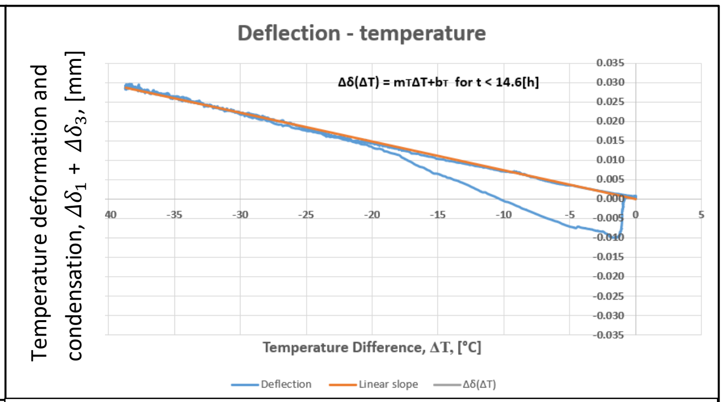


Figure 3.2.1-1



Temperature dependent deformation:

$$\Delta\delta_1(\Delta T) = m_T \Delta T + b_T \text{ [mm]} \qquad \text{for t < 14.6[h]}$$
$$= -0.00074\Delta T + 0.00001$$

TEMPERATURE CYCLE 1-TEST 2

Table 3.2.1-2

TEMPERATURE CYCLE 1-TEST 1 14-15 December 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil reflector and vacuum grease						
Time, t [h]	1	3	3	3	3	3+
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.2	9.9	-1.5	-10.5	-19.6	19.0
$\Delta\delta_1 + \Delta\delta_3$ [μm]	0.8	7.3	12.6	19.4	24.6	-1.8

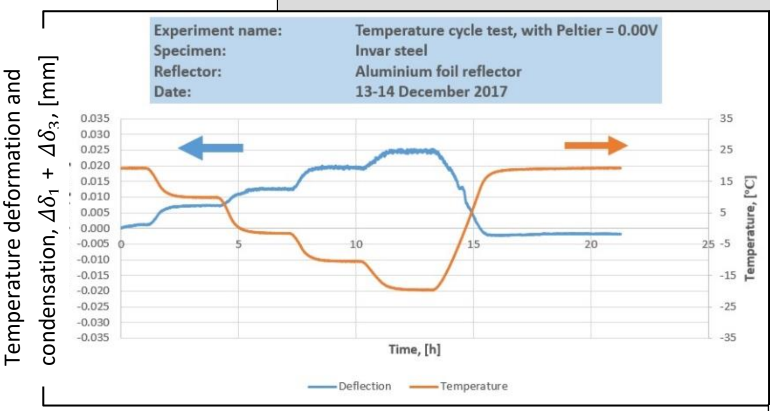
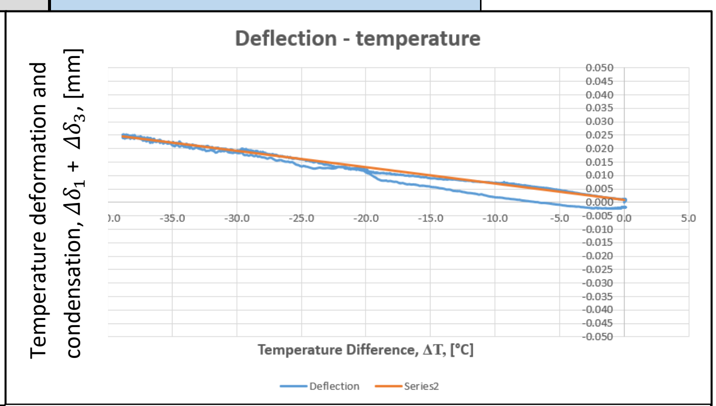


Figure 3.2.1-2



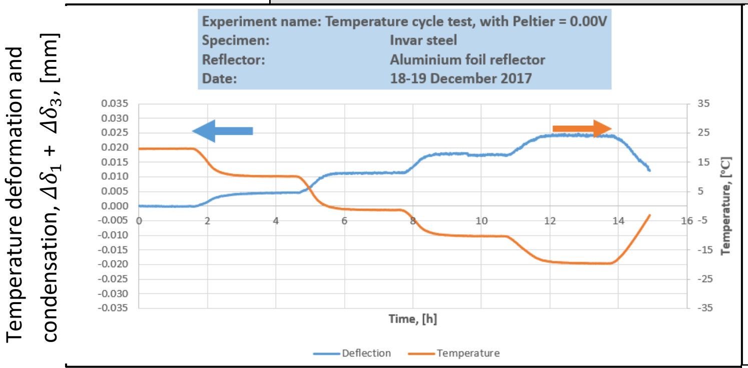
Temperature dependent deformation:

$$\Delta\delta_1(\Delta T) = m_T \Delta T + b_T \text{ [mm]} \qquad \text{for t < 14.6[h]}$$
$$= -0.00061\Delta T + 0.00096$$

TEMPERATURE CYCLE 1-TEST 3

Table 3.2.1-3

TEMPERATURE CYCLE 1-TEST 1 18-19 November 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil reflector and vacuum grease						
Time, *t* [h]	1	3	3	3	3	3+
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.6	10.1	-1.4	-10.3	-19.1	N/A
$\varDelta\delta_1 + \varDelta\delta_3$ [μm]	-0.1	4.5	11.4	17.5	24.0	N/A



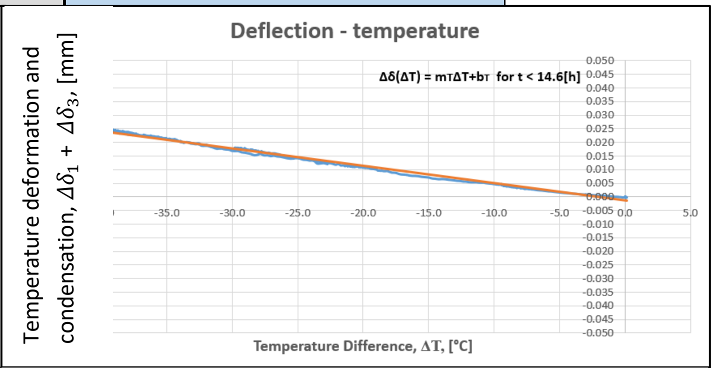


Figure 3.2.1-3

Temperature dependent deformation:

$\varDelta\delta_1(\varDelta T) = m_T \varDelta T + b_T$ [mm] for t < 14.6[h]

$= -0.00063\varDelta T - 0.00120$

3.2.2 DRIFT $\Delta\delta_2$

TEMPERATURE CYCLE 2 - TEST 1

Table 3.2.2-1

TEMPERATURE CYCLE 1-TEST 1 13-16 October 2017 – Constant temperature at +20 [°C] Specimen: Invar steel, with aluminum foil reflector and vacuum grease	
Time, t [h]	64
REAL temperature, over beam, $T_{specimen,above}$ [°C]	20.7
Maximum $\Delta\delta_2$ [μm]	1.3

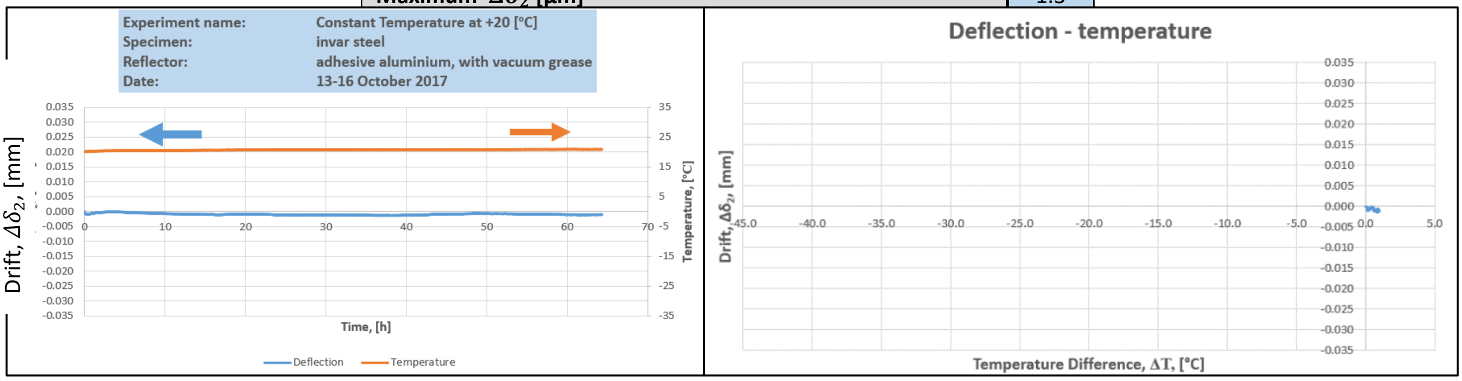


Figure 3.2.2-1

TEMPERATURE CYCLE 2 - TEST 2

Table 3.2.2-2

TEMPERATURE CYCLE 1-TEST 2 11-12 November 2017 – Constant temperature at +20 [ºC] Specimen: Invar steel, with aluminum foil reflector and vacuum grease	
Time, t [h]	16
REAL temperature, over beam, $T_{specimen,above}$ [°C]	0.2
Maximum $\Delta\delta_2$ [μm]	0.4

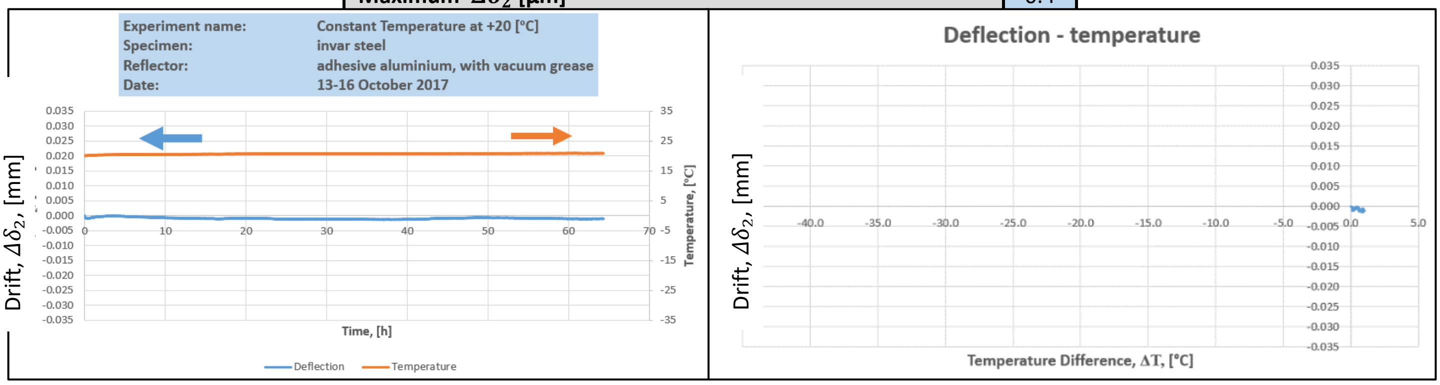


Figure 3.2.2-2

3.3 PHASE 3: COMPOSITE TESTS

The results below measures the bi-material deflection of **composite specimen 2.1** only. Specimen 1.1 and 3.1 are not shown here. Specimen 1.1 got damaged. The results of specimen 3.1 are given in Appendix C.

TEMPERATURE CYCLE 1: FROM +20[ºC] to +10[ºC]

Table 3.3-1

TEMPERATURE CYCLE 1 8 December 2017			
Time, t [h]	1	3	5
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.1	10.3	19.6
Deflection of the specimen, $\delta_{specimen}$[μm]	0.1	10.7	0.0

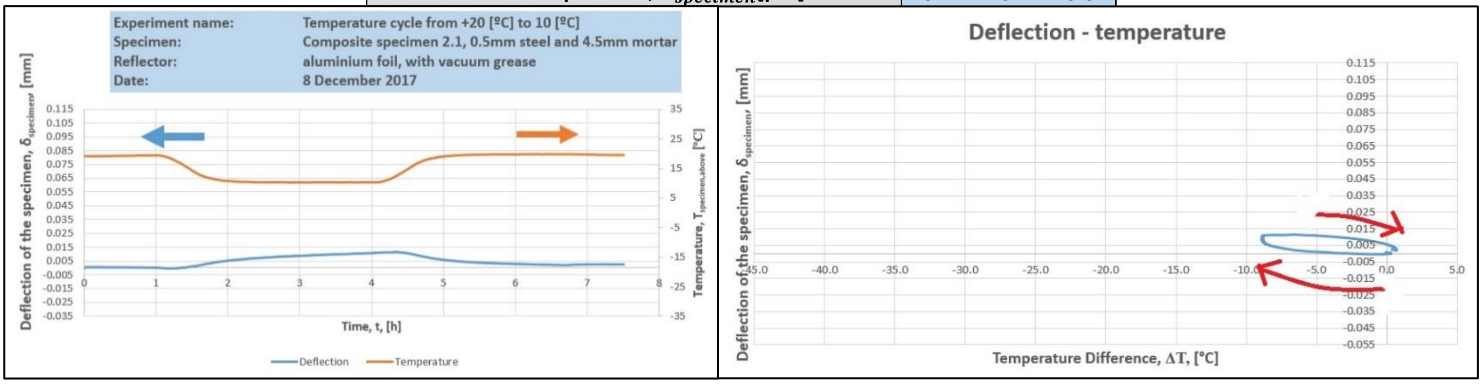


Figure 3.3-1

TEMPERATURE CYCLE 2: FROM +20[ºC] to 0[ºC]

Table 3.3-2

TEMPERATURE CYCLE 2 8-9 December 2017				
Time, t [h]	1	3	3	11.5
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.5	10.1	-1.8	19.9
Deflection of the specimen, $\delta_{specimen}$[μm]	-0.5	8.3	21.1	0.8

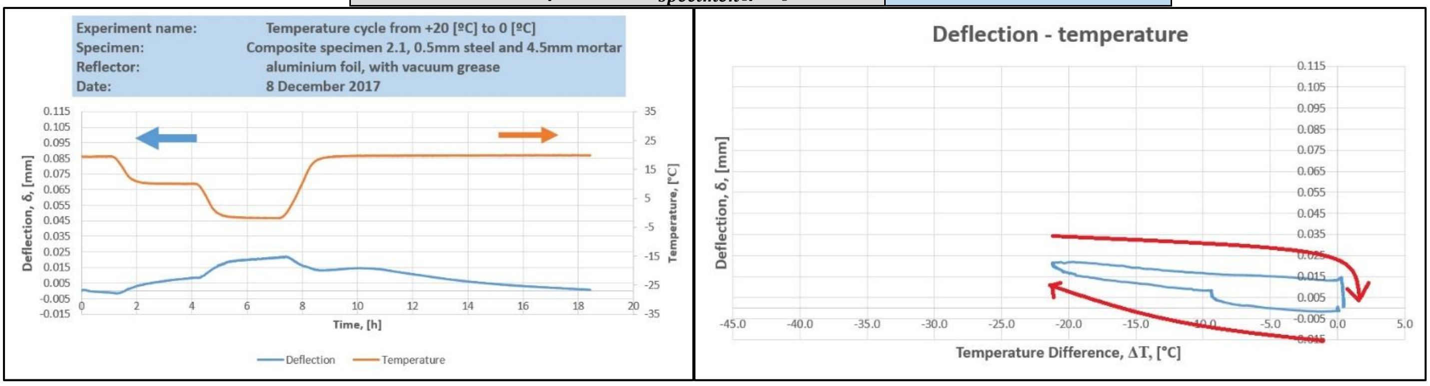


Figure 3.3-2

TEMPERATURE CYCLE 3: FROM +20[ºC] to -10[ºC]

Table 3.3-3

TEMPERATURE CYCLE 3 9-10 December 2017					
Time, t [h]	1	3	3	3	5
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.8	10.7	-0.7	-9.6	20.4
Deflection of the specimen, $\delta_{specimen}$[µm]	-1.4	8.4	23.0	32.1	-5.0

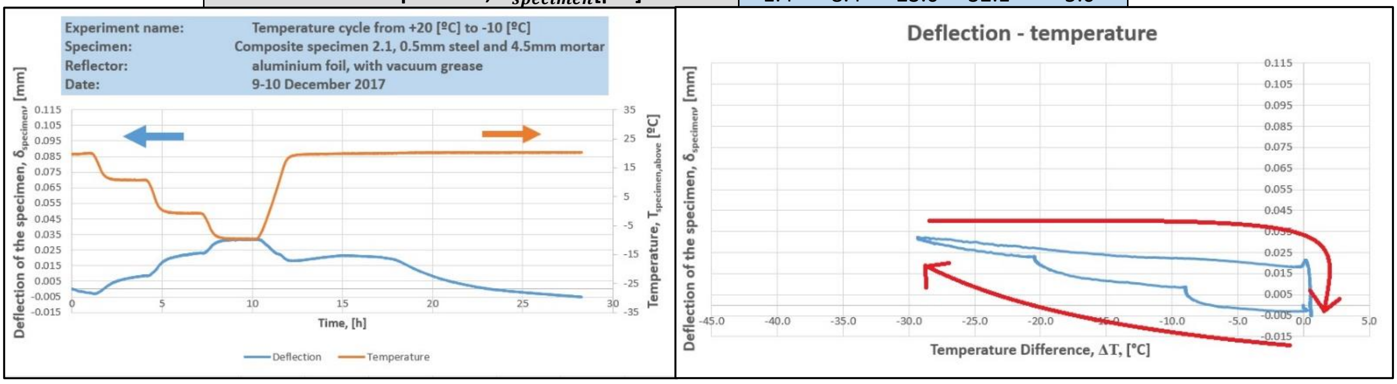


Figure 3.3-3

TEMPERATURE CYCLE 4: FROM +20[ºC] to -20[ºC]

Table 3.3-4

TEMPERATURE CYCLE 4 10-11 December 2017						
Time, t [h]	1	3	3	3	3	5
REAL temperature, over beam, $T_{specimen,above}$ [°C]	20.3	10.8	-0.7	-9.7	-19.2	19.1
Deflection of the specimen, $\delta_{specimen}$[µm]	-0.5	7.9	25.2	37.1	47.8	N/A

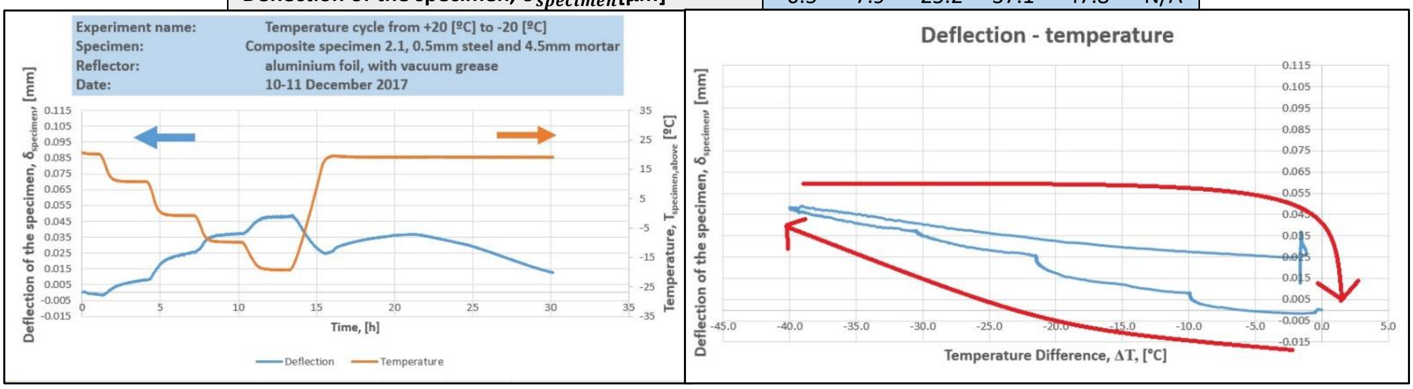


Figure 3.3-4

After all the four temperature cycles were completed, specimen 2.1 was removed from the freeze-warping box and inspected. No visible frost damage was observed.

4 ANALYSIS and DISCUSSION

4.1 PHASE 1: FINDING THE SETTING FOR THE PELTIERS AND JULABO

Refer to Appendix B.

4.2 PHASE 2: DEFORMATION AND DRIFT TESTS

TENOERATYRE CYCLE 1 - TEST 1, 2 and 3

Description:

The figures in *chapter 3.2.1* show the results of three temperature cycle tests. The **temperature dependent deformation** $\boldsymbol{\Delta\delta_1}$ plus **condensation** $\boldsymbol{\Delta\delta_3}$ are measured during a stepwise temperature cycle experiment from +20[ºC] to -20[ºC] in four steps, then heated up to +20[ºC]. The first 4 steps have a duration of 3 [h] to give the specimen enough time to reach a temperature equilibrium. The results for all three tests are discussed below:

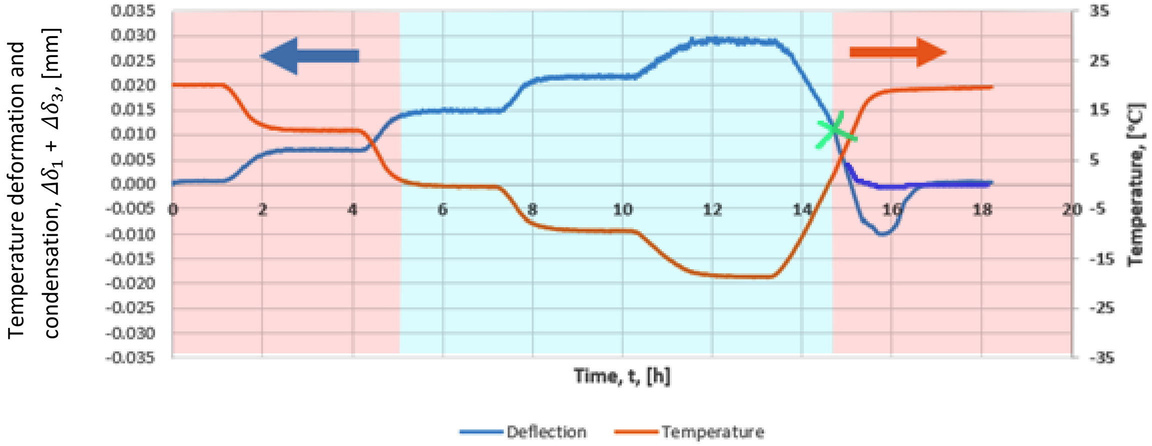


Figure 4.2-1 Figure 3.2.1-1 from test 1, Figure 3.2.1-2 from test 2 and Figure 3.2.1-3 from test 3 are combined.

-The pink area shows when the specimen was above 0 [ºC],

-The blue area shows when the specimen was below 0 [ºC]

Between 0[h] and 14.6 [h],

The relation between the temperature dependent deformation $\Delta\delta_1$ and the specimen's temperature difference ΔT is linear. This linear relation is expressed as: $\Delta\delta_1(\Delta T) = m_T\Delta T + b_T$. All three tests had similar slopes m_T and intercepts b_T.

Between 5[h] and 14.6 [h],

The temperature in the freeze-warping box is below 0 [ºC]. Ice is accumulating outside and inside the freeze-warping box for all three tests.

Beyond 14.6 [h],

The temperature $T_{specimen,above} > 0$ [°C], and the ice begins to melt, and moisture begins to collect inside the freeze-warping box for all three tests. The effects of condensation***** vary for each three tests.

*****A test (not mentioned in 3 Results) was performed in which the freeze-warping box was brought down from 20 [ºC] to below 0 [ºC] for several hours. Then the temperature was increased back to 20 [ºC]. Before the condensation dried away, the specimen was removed from the freeze-warping box, and inspected. It was observed that condensation had collected on the reflector tab.

- Test 1: Figure 4.2-1 (blue line) between 15[h] and 17[h] shows a noticeable dip in the Deflection-Temperature curve (also check Figure 3.2.1-1). It is assumed to be caused by condensation covering the reflector tab. This means the vacuum grease did not sufficiently prevent condensation from collecting on the reflector tab.
- Test 2: Figure 4.2-1 (dark blue line) between 15[h] and 17[h] shows a very subtle dip in the Deflection-Temperature curve (also check Figure 3.2.1-2). Some condensation may have covered the reflector tab. There was slightly more vacuum grease on the reflector tab for test 2 than there was in test 1. This means the vacuum grease did a better job at preventing condensation from collecting on the reflector tab.
- Test 3: Beyond 14.6 [h], catman®Easy stopped working. This is marked in Figure 4.2-1 with a green X. Data beyond this point never got logged. The effect of any possible condensation collecting on the reflector tab did not get recorded.

CONSTANT TEMPERATURE CYCLE 1-TEST 1 and 2

The figures in *chapter 3.2.2* show the results of two temperature cycle tests. The **drift $\boldsymbol{\Delta\delta_2}$** was measured during a constant temperature cycle at +20[ºC]. Both tests showed minimal drift.

DRIFT AND DEFORMATION $\Delta\delta(\Delta T)$

- **Temperature dependent deformation $\boldsymbol{\Delta\delta_1}$:** The orange lines on the deformation-temperature curves in Temperature cycle *1 – test 1, 2 and 3* (chapter 3.2.1) show a linear relation between $\Delta\delta_1$ and the specimen's temperature difference ΔT. This linear relation is expressed as the average of the three temperature cycles:

$$\Delta\delta_1(\Delta T) = m_T \Delta T + b_T [mm], \qquad \text{t < before accumulated ice melts [h]}$$

$$m_T = -0.00066 = \frac{-0.00074 - 0.00061 - 0.00063}{3} \qquad [mm/℃]$$

$$b_T = -0.00008 = \frac{0.00001 + 0.00096 - 0.00120}{3} \qquad [mm]$$

- **Drift $\boldsymbol{\Delta\delta_2}$:** the results from *temperature cycle 2-test 1 and 2* showed drift. Drift has a negligible contribution to the total drift and temperature dependent deformation", $\Delta\delta_2 \approx 0[\mu m]$
- **Condensation $\boldsymbol{\Delta\delta_3}$:** *Temperature cycle 1 – test 1 and 2* are the only results that showed the effects of condensation. The effects of condensation vary greatly between the two tests. There are not enough results to make an equation to express the size of $\Delta\delta_3$.

The **drift and temperature dependent deformation $\boldsymbol{\Delta\delta}$** is given as:

$$\boxed{\begin{aligned} &\Delta\delta(\Delta T) = \Delta\delta_1 + \Delta\delta_2 + \Delta\delta_3 \\ &\qquad = -0.00066\Delta T + -0.00008 + \Delta\delta_3\ [\mu m] \\ &\Delta\delta_3 \begin{cases} = 0\ [mm], before\ ice\ melts \\ \leq 0\ [mm], after\ ice\ melts. \end{cases} \end{aligned}}$$

4.3 COMPOSITE TESTS (PHASE 3)

For all four *temperature cycle tests*(chapter 3.3), the deflection of the specimen $\delta_{specimen}$ [μm] is measured as:

$$\delta_{specimen} = \delta - (-0.00066\Delta T + -0.00008)\ [\mu m]$$

(The condensation $\Delta\delta_3$ is not subtracted since we have not found a proper expression for it.)

The figures in *chapter 3.3* show four different temperature cycle tests, and measures the bi-material deflection $\delta_{specimen}$ of a steel-mortar composite specimen. The deflection is measured during a stepwise temperature cycle experiment from:

- Temperature cycle 1: from +20[ºC] to +10[ºC], then heated up to +20[ºC].
- Temperature cycle 2: from +20[ºC] to 0[ºC], then heated up to +20[ºC].
- Temperature cycle 3: from +20[ºC] to -10[ºC], then heated up to +20[ºC].
- Temperature cycle 4: from +20[ºC] to -20[ºC], then heated up to +20[ºC].

MODELING TIMOSHENKO-SCHERER/VALENZA

The figure below illustrates all measured bi-material deflections $\delta_{specimen}$[μm] from Temperature cycle 1-4 (Figure 3.3-1 to 3.3-4), and compares it Scherer/Valenza's **bi-material bending model** (equation 2.8). Their model is shown in the figure as dashed lines. There is an upper and lower limit that takes the specimen's uneven mortar thickness into consideration.

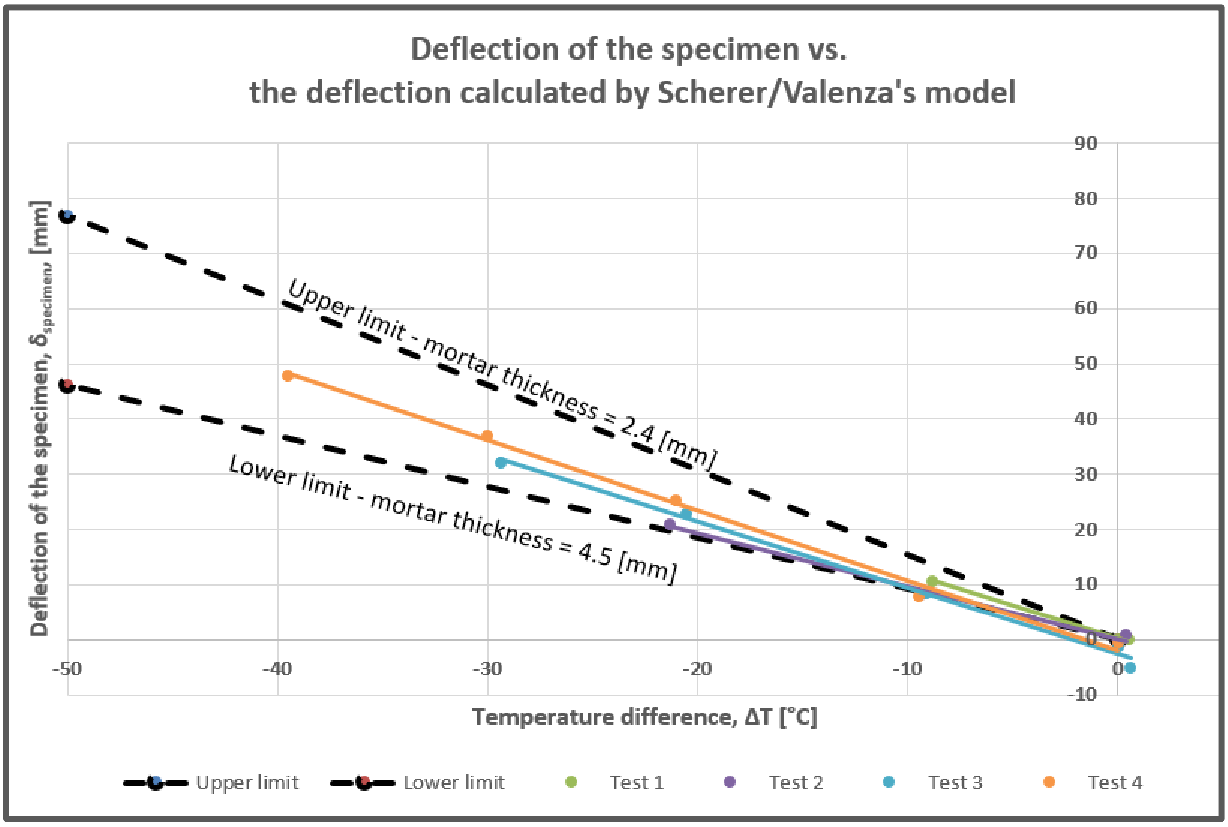
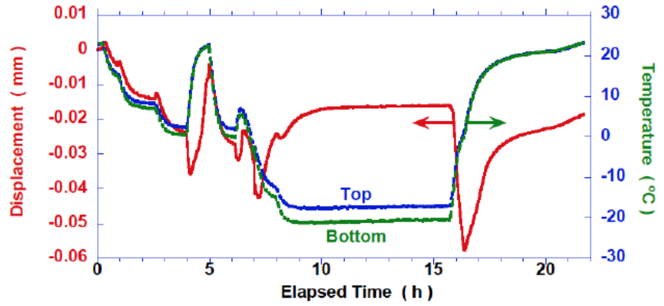


Figure 4.3-1 Bi-material deflections $\delta_{specimen}$ vs. the temperature difference of the specimen $\Delta T = T_{specimen,above.\ time=t[h]} - T_{specimen,above.\ time=0[h]}$

The figure shows that the measured deflection $\delta_{specimen}$ fits well between the **Upper Limit** and **Lower Limit** (dashed lines).

RESULTS FROM JACOBSEN AND SCHERER'S FREEZE-WARPING BOX EXPERIMENT



a)

Figure 5: a) Measured temperature (right ordinate) and deflection (left ordinate) of air-entrained mortar/steel composite;

Figure 4.3-2 Displacement/deflection $\delta_{specimen}$ vs Time curve and Temperature vs Time curve

(*NOTE: Scherer and Jacobsen attached the reflector tab on their specimen's mortar side, which results in a **downward** deflection. The specimen in chapter 3.3 had the reflector tab attached to the specimen's steel side. This resulted in an upward deflection.

Scherer and Jacobsen have also used a different temperature cycle than the one in chapter 3.3)

(The figure is from Jacobsen and Scherer's paper [4.1])

Figure 4.3-2 shows the results from Jacobsen and Scherer's experiment with a temperature cycle from +20 [°C] to -20[°C]. They measured the composite's deflection as $\delta_{specimen} \approx -15[\mu m]$ at $\Delta T = -40[C]$. This is well below the *Lower Limit* line in Figure 4.3-1.

At $\Delta T = -40[C]$, the temperature dependent deformation $\Delta\delta_1 \approx +26[\mu m]$. <u>If</u> it is assumed that Jacobsen and Scherer's results did not take $\Delta\delta_1$ into account, the real deflection would show that $\delta_{specimen} \approx -15 - 26 = -41[\mu m]$. This will then fit very closely to the Lower Limit line in Figure 4.3-1.

The bi-material deflection measured in chapter 3.3, the bi-material bending model, and measured in Jabosen and Scherer's experiment, are all very close. <u>It is therefore concluded that the freeze-warping box at NTNU gives reliable measurements.</u>

4.4 SOURCE OF ERROR

The following errors were made:

- In phase 2: *Temperature cycle 1 – test 1*

  The data logging program catman®Easy stopped working mid-way through the test. The lack of data after 14.6[h] prevented us from getting information about the effects of condensation collecting on the reflector tab.
- In phase 3: *Temperature cycle 4: from +20[ºC] to -20[ºC]*

  The deflection-time curve in Figure 3.3-5 shows that the deformation has not reached equilibrium after 30 [h]. The test should have been given more time for the deformation to reach equilibrium. It was not given enough time to conclude with certainty if the composite specimen endured any permanent deformation/frost damage.

5 CONCLUSIONS

5.1 RECOMMENDED MEASURES AND FUTURE WORK

EQUIPMENT'S SENSITIVITY TO SURROUNDINGS

The optic probe's reading I [V] can measure a specimen's deflection $\delta_{specimen}$ [mm] with a very high precision if used properly. This reading is highly sensitive to its surroundings. It was suspected that the measured $\delta_{specimen}$ could be affected by the following sources of vibrations:

(1) Construction work outside
(2) The vibration caused by Julabo, and the cooling liquid circulating the tubes
(3) The opening and closing of the table's drawers that the freeze-warping box is standing on
(4) The vibrations from the fotonic sensors
(5) Other people walking, stomping, moving things on/off the table, or bumping onto the table with the freeze-warping box

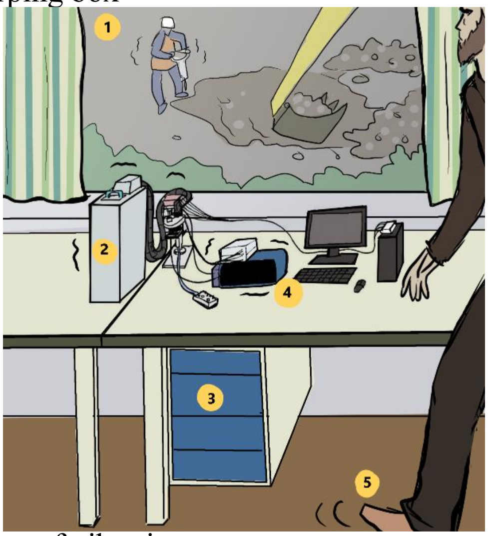


Figure 5.1-1 Sources of vibration

Julabo is placed on a separate table from the fotonic sensor, which helps to reduce the effects of Julabo's vibrations. The drift tests in Chapter 3.2.2 and 4.2, and Appendix B.1.4 showed minimal drift. In Chapter 3.2.2, the only sources of vibrations were Julabo (2) and the fotonic sensor (3). Appendix B.1.4 had no sources of vibrations. Both Chapter 3.2.2 and Appendix B.1.4 showed negligible drift. We can therefore ignore (2) and (4).

During the making of this thesis, multiple attempted freeze-warping box experiments had to be discarded due to disturbances caused by (1), (2) and (3). The following measures are recommended to reduce the effect from the freeze-warping box's surroundings:

- place the freeze-warping box (and Julabo) on vibration free tables.
- place the freeze-warping box in a room that gets few visitors.

RELIABILITY OF THE LAB EQUIPMENT

Some of the lab equipment (most notably Julabo) have been very unreliable. Julabo has frequently shut down mid-way through an experiment. One of the main causes is the rapid evaporation rate of the cooling liquid (ethanol). (Roughly 1 liter evaporates each day!) After a discussion with Stefan Jacobsen (advisor), the following measure was made:

- butyl tape was added around the rim of Julabo's lid.

This measure helped to reduce the evaporation rate of ethanol substantially, however the evaporation rate is still high. (Roughly 0.5 liter evaporates each day). Julabo still shuts down frequently, even if there is enough cooling liquid. The causes are unknown.

After several discussions with the people at the laboratories of *Department of Structural Engineering,* we concluded that the following measures are recommended for future freeze-warping box experiments:

- use a different cooling liquid than ethanol, such as glycol that has a higher boiling point. This will reduce the evaporation rate of the cooling liquid.
- <u>OR</u> use a different refrigerated/heating circulator that is more reliable.

THE SPECIMEN'S TEMPERATURE AS A FUNCTION OF THE SETTING ON JULABO AND THE PELTIERS

In Chapter 3.1.1 and Chapter 3.1.2, the following expression for the specimen's temperature was found:

- When the temperature is controlled by the Peltiers:

$$T_{specimen,above} = \begin{cases} -3.0822V_{Peltier} - 19.984 \; for \; T_{Julabo} = 20[°C] \\ -2.47347V_{Peltier} - 4.317 \; for \; T_{Julabo} = -12.50[°C] \end{cases} \quad (4.1)$$

  Where $T_{Julabo} \geq -20[°C]$

- When the temperature is controlled by Julabo:

$$T_{specimen,above} = \begin{cases} -0.706T_{Julabo} - 6.4832 \; for \; V_{Peltier} = 5.70[V] \\ -0.6433T_{Julabo} - 10.964 \; for \; V_{Peltier} = -0.00[V] \end{cases} \quad (4.2)$$

(4.1) and (4.2) expresses the specimen's temperature as a function of one variable. It is more practical to work with one expression for the specimen's temperature as a function of two variables: $T_{specimen,above}(V_{Peltier}, T_{Julabo})$.

From (4.2) the slope and the intercept seem to be dependent on the Peltiers' setting $V_{Peltier}$. From (4.1) the slope and the intercept seem to be dependent on Julabo's setting T_{Julabo}. For future work, to find the expression for $T_{specimen,above}(V_{Peltier}, T_{Julabo})$, it is recommended to run all temperature cycle described in the tables below, three times each.

Table 5.1-1 Recommended temperature cycles for finding $T_{specimen,above}(V_{Peltier}, T_{Julabo})$

Time, t [h]	1	3	3	3	3	3	3	3
Julabo, T_{Julabo} [°C]	50	40	30	20	10	0	-10	-20
Peltier, $V_{Peltier}$ [V]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Time, t [h]	1	3	3	3	3	3	3	3
Julabo, T_{Julabo} [°C]	50	40	30	20	10	0	-10	-20
Peltier, $V_{Peltier}$ [V]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Time, t [h]	1	3	3	3	3	3	3	3
Julabo, T_{Julabo} [°C]	50	40	30	20	10	0	-10	-20
Peltier, $V_{Peltier}$ [V]	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Time, t [h]	1	3	3	3	3	3	3	3
Julabo, T_{Julabo} [°C]	50	40	30	20	10	0	-10	-20
Peltier, $V_{Peltier}$ [V]	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Time, t [h]	1	3	3	3	3	3	3	3
Julabo, T_{Julabo} [°C]	50	40	30	20	10	0	-10	-20
Peltier, $V_{Peltier}$ [V]	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Time, t [h]	1	3	3	3	3	3	3	3
Julabo, T_{Julabo} [°C]	50	40	30	20	10	0	-10	-20
Peltier, $V_{Peltier}$ [V]	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Time, t [h]	1	3	3	3	3	3	3	3
Julabo, T_{Julabo} [°C]	50	40	30	20	10	0	-10	-20
Peltier, $V_{Peltier}$ [V]	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00

WORK ENVIRONMENT

During a freeze-warping box test, the ethanol in Julabo evaporates. The freeze-warping box's surrounding area will therefore have a strong smell of ethanol. It is not dangerous, but it is uncomfortable. It is advised that the person operating the freeze-warping box stays in a separate room whenever possible.

PELTIERS VS. JULABO

There are mainly two ways to control the temperature in the freeze-warping box;

- by adjusting Julabo's temperature setting T_{Julabo}
- by adjusting the Peltier's voltage setting $V_{Peltier}$

There are pros and cons to each of these two methods. <u>It is more practical to control the temperature cycle with Julabo.</u> It is possible to program a temperature cycle on Julabo, which means the person operating the freeze-warping box only needs to visit it before and after a temperature cycle. When the specimen's temperature is controlled with the Peltiers, its settings must be adjusted manually, which means the person operating the freeze-warping box has stay within proximity of the lab equipment.

The overall <u>temperature cycle's duration takes longer when it is controlled by Julabo</u>, rather than the Peltier. <u>Ethanol evaporates more quickly when it is controlled by Julabo</u>, because higher temperature settings on Julabo T_{Julabo} are required to reach the correct specimen temperature $T_{specimen,above}$. It is possible to connect the Peltier's power supplies to a computer via a USB cable. It is therefore recommended to <u>setup a computer program that can control the Peltiers' setting automatically.</u>

PREPARATIONS OF THE SPECIMENS

The dry concrete specimens (see chapter 2.1) were entirely covered with vacuum grease. After discussions with Stefan Jacobsen, it was suggested that they were prepared differently:
Only the reflector tab should be covered with vacuum grease to prevent condensation from collecting on it. The rest of the specimen is covered with plastic wrap held in place with rubber bands.
This preparation method is less invasive. The recommended procedures in Appendix A.1 shows Stefan Jacobsen's suggested preparation method, NOT the method used in 2.1.2.

RELIABILTY OF THE MEASURED BI-MATERIAL DEFLECTION

The drift tests in chapter 3.2.2 (Figure 3.2.2-1 and Figure 3.2.2-2) showed minimal drift when an invar steel specimen was set at a constant temperature of $T_{specimen,above} = 20[°C]$. There is a possibility that the drift is temperature dependent. It is therefore recommended to run more drift tests at a constant temperature of $T_{specimen,above} = -20[°C]$.

COMPOSITE SPECIMEN 2.1

From 3.2.2, it is unknown if specimen 2.1 endured any permanent frost damage after undergoing temperature cycles 1-4. It is recommended to check this by repeating Temperature cycle 1: from $+20[°C]$.to +$10[°C]$, and then see if it the deformation is the same as what was found in Figure 3.3-1.

6 REFERENCES

1 INTRODUCTION

[1.1] BYGGFORSK. Jacobsen, S. (1999). Betong Frostnedbrytning av betong og andre porøse byggematerialer. Kolbotn: Nikolai Olsens Trykkeri AS, pp. 1, 3.

[1.2] Sellevold E. (2016). Chapter 15 – Frost deterioration. In: S. Jacobsen, TKT 4215 Concrete Technology. Trondheim, 2016 ed. NTNU: Department of Structural Engineering, pp. 3-5

[1.3] Myrdal, R. (2016). Chapter 10 – Admixtures. In: S. Jacobsen, TKT 4215 Concrete Technology. Trondheim, 2016 ed. NTNU: Department of Structural Engineering, page. 11.

[1.4] Valenza, J. and Scherer.G (2005). Mechanism for Salt Scaling. Princeton University, pp. 220-223 and 232

2 METHODS

[2.1] Jacobsen, S., and Scherer, G. (2016). Freezing Induced Stresses in Concrete Composite Beams and Effects of Air Voids. In: International RILEM Conference on Materials, Systems and Structures in Civil Engineering, Conference segment on Frost action in concrete. Lyngby: Technical University of Denmark, pp.2-3 and 6-9

[2.2] Valenza, J. and Scherer.G (2005). Mechanism for Salt Scaling. Princeton University, pp. 220-223 and 232

[2.3] MTI Instruments Inc 2000. User's Manual MTI-2000 Fotonic™Sensor DOCUMENT ID: A0401 Revision 2.3, Manual, MTI Instruments Inc., Washington

4 ANALYSIS and DISCUSSION

[4.1] Jacobsen, S., and Scherer, G. (2016). Freezing Induced Stresses in Concrete Composite Beams and Effects of Air Voids. In: International RILEM Conference on Materials, Systems and Structures in Civil Engineering, Conference segment on Frost action in concrete. Lyngby: Technical University of Denmark, pp.2-3 and 6-9

APPENDIX A

Manuals:

[A.1]Marlow Industires, Inc.®. 2005 Thermoelectric Cooler DT12-9, Manual, Marlow Industtries, Inc. Dallas Texas

[A.2]Julabo The Temperature Control Company. 2006, Operating Manual Refrigerated and Heating Cirvulators F33-MA, Julabo, Allentown

[A.3]MTI Instruments Inc 2000. User's Manual MTI-2000 Fotonic™Sensor DOCUMENT ID: A0401 Revision 2.3, Manual, MTI Instruments Inc., Washington

Videos:

[A.4]Untitled video about how to calibrate the fotonic sensor and optic probe, shared by Andrei Shpak and Ole Christian Børsum

7 List of Symbols

Symbol	**Definition**	**Unit**	**Page**
	1 INTRODUCTION		
$\delta_{specimen}$	Bi-material deflection of a composite specimen	[mm]	1-2
$T_{specimen}$	Specimen's temperature	[°C]	1-4
T_{Julabo}	Julabo's temperature setting	[°C]	1-4
$V_{Peltiers}$	Peltiers' voltage setting	[V]	1-4
Δt	Time	[h]	1-4
$\Delta\delta$	Drift and temperature deformation of the freeze-warping box.	[mm]	1-4
	2 METHODS		
t_1	Height of a composite specimen's top layer	[mm]	2-5
t_2	Height of a composite specimen's bottom layer	[mm]	2-5
w_1	Width a composite specimen's top layer	[mm]	2-5
w_2	Width of a composite specimen's bottom layer	[mm]	2-5
L	Length of a composite specimen	[mm]	2-5
E_1	Elastic modulus of material 1	$[Nmm^{-2}]$	2-5
E_2	Elastic modulus of material 2	$[Nmm^{-2}]$	2-5
α_1	Coefficient of thermal expansion (CTE) of material 1	[°C^{-1}]	2-5
α_2	Coefficient of thermal expansion (CTE) of material 1	[°C^{-1}]	2-5
d	Displacement of the LVDT AND the distance between the optic probe's head and the specimen's reflector tab	[mm]	2-8
I	The reading of the optic probe	[V]	2-9
δ	Measured deflection. $\delta = \delta specimen + \Delta\delta = d2 - d1$	[mm]	2-9
$T_{air,inside}$	Temperature of the air inside the copper box. (A TC is attached under the copper box's lid, measuring the temperature of the air inside the freeze-warping box, above the specimen.)	[°C]	2-11
$T_{air,outside}$	Temperature of the air outside the freeze-warping box. (A TC is attached to the insulation lid, measuring	[°C]	2-11

	the temperature of the air above the freeze-warping box-)		
$T_{specimen,above}$	Temperature of the specimen. (A TC is touching the upper side of a specimen, measuring the specimen's temperature.)	[℃]	2-11
T_{inlet}	Temperature of the cooling liquid. (A TC is attached to the water inlet; the tube's inflowing end where it meets the aluminum block.)	[℃]	2-11
$T_{Peltier,cold}$	Temperature of the Peltier's cold side. (A TC is attached to the cold side of the Peltier.)	[℃]	2-11
I_{optic}	The reading of the optic probe	[V]	2-12
m	Slope of Range 1 or 2	[V/mm]	2-13
b	Intercept of Range 1 or 2	[V]	2-13
$\mathbf{m_1}$	Slope of Range 1	[V/mm]	2-13
$\mathbf{b_1}$	Intercept of Range 1	[V]	2-13
$\mathbf{m_2}$	Slope of Range 2	[V/mm]	2-13
$\mathbf{b_2}$	Intercept of Range 2	[V]	2-13
$\delta_{specimen}$	Bi-material deflection of the specimen	$[mm]$	2-13
$\Delta\delta$	Drift and temperature dependent deformation $\Delta\delta = \Delta\delta 1 + \Delta\delta 2 + \Delta\delta 3$	$[mm]$	2-13
$\Delta\delta_1$	Drift	$[mm]$	2-14
$\Delta\delta_2$	Temperature dependent deformation of the freeze-warping box's system	$[mm]$	2-14
$\Delta\delta_3$	Condensation	$[mm]$	2-14
W_B	Deflection span of the specimen	$[mm]$	2-14
d_1	Distance between the specimen and the optic probe, before the freeze-thaw cycle	$[mm]$	2-14
d_2	Distance between the specimen and the optic probe, during the freeze-thaw cycle.	$[mm]$	2-14
m_T	Slope of the function: $\Delta\delta_1(\Delta T)=m_T\Delta T+b_T$	$[mm/℃]$	2-20
b_T	Intercept of the function: $\Delta\delta_1(\Delta T)=m_T\Delta T+b_T$	$[mm]$	2-20
K_R	Curvature	$[mm{-}1]$	2-22

$\boldsymbol{\Delta\varepsilon_f}$	Strain between the two material surfaces	[−]	2-22
$\boldsymbol{T_{specimen,1}}$	The specimen temperature before a temperature cycle	[°C]	2-23
$\boldsymbol{T_{specimen,2}}$	The specimen's temperature during a temperature cycle	[°C]	2-3
3 RESULTS			
$\boldsymbol{T_{Julabo}}$	Julabo's temperature setting	[°C]	3-2
$\boldsymbol{V_{Peltiers}}$	Peltiers' voltage setting	[V]	3-2
$\boldsymbol{T_{specimen,above}}$	Temperature of the specimen. (A TC is touching the upper side of a specimen, measuring the specimen's temperature.)	[°C]	3-2
$\boldsymbol{\Delta\delta_1}$	Temperature dependent deformation of the freeze-warping box's system	$[mm]$	3-4
$\boldsymbol{\Delta\delta_3}$	Condensation	$[mm]$	3-4
$\boldsymbol{m_T}$	Slope of temperature dependent deformation	$[mm$ $/°C]$	3-4
$\boldsymbol{b_T}$	Intercept of temperature dependent deformation	$[mm]$	3-4
$\boldsymbol{\Delta T}$	Temperature difference of the specimen = $T_{specimen,above}(t) - T_{specimen,above}(t = 0[h])$	[°C]	3-4
$\boldsymbol{t}$	Time	[h]	3-4
$\boldsymbol{\Delta\delta_2}$	Drift	[mm]	3-6
$\boldsymbol{\delta_{specimen}}$	Deflection/bending of the specimen	$[mm]$	3-7
4 ANALYSIS and DISCUSSION			
$\boldsymbol{\Delta\delta_1}$	Temperature dependent deformation	$[mm]$	4-2
$\boldsymbol{\Delta\delta_3}$	Condensation	$[mm]$	4-2
$\boldsymbol{T_{specimen,above}}$	Temperature of the specimen. (A TC is touching the upper side of a specimen, measuring the specimen's temperature.)	[°C]	4-2
$\boldsymbol{\Delta T}$	Temperature difference of the specimen = $T_{specimen,above}(t) - T_{specimen,above}(t = 0[h])$	[°C]	4-2
$\boldsymbol{m_T}$	Slope of temperature dependent deformation	$[mm$ $/°C]$	4-2

$\boldsymbol{b_T}$	Intercept of temperature dependent deformation	$[mm]$	4-2
$\boldsymbol{\Delta\delta_1}$	Drift	$[mm]$	4-3
$\boldsymbol{\Delta\delta}$	Drift and temperature dependent deformation	$[mm]$	4-3
$\boldsymbol{\delta_{specimen}}$	Deflection/bending of the specimen	$[mm]$	4-3
5 CONCLUSIONS			
$\boldsymbol{\Delta T}$	Temperature difference of the specimen = $T_{specimen,above}(t) - T_{specimen,above}(t = 0[h])$	[°C]	5-3
$\boldsymbol{T_{Julabo}}$	Julabo's temperature setting	[°C]	5-3
$\boldsymbol{V_{Peltiers}}$	Peltiers' voltage setting	[V]	5-3
$\boldsymbol{t}$	Time	[h]	5-3

8 List of Figures

9 List of Tables

Appendix A

Recommended Procedure

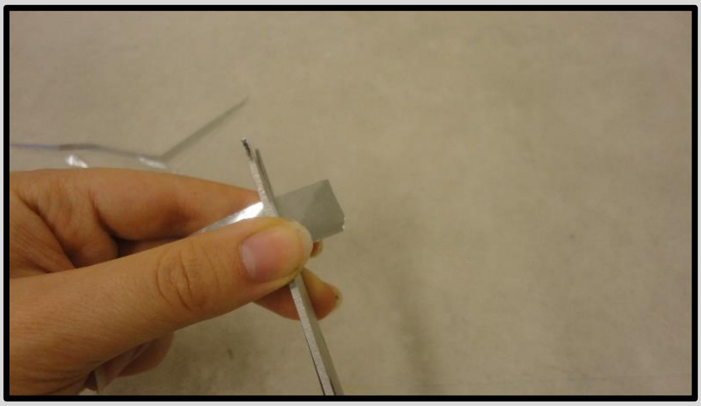
A.1 PREPARPING SPECIMENS FOR THE FREEZE-WARPING BOX

A step-by-step guide on how to prepare the freeze-warping box specimens is provided down below.

Steps 1)-6) applies for all types of specimens
Steps 7) and onwards applies for concrete specimens which moisture content cannot be altered by its surroundings.

1) Get some aluminum foil

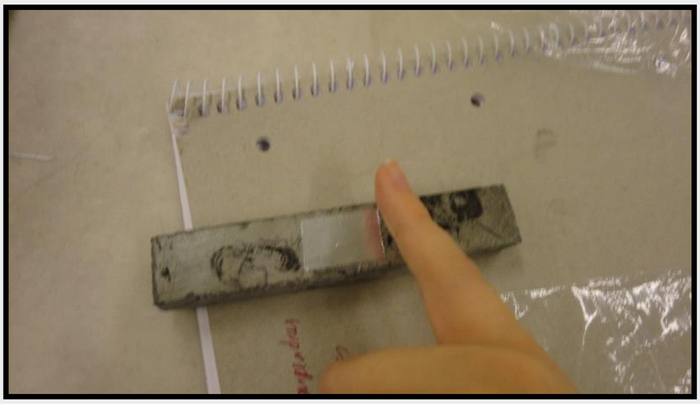
2) Carefully roll it out on a clear and flat table. Its matte side should be facing down.



3) Use scissors to cut a reflector tab.

4) Use a glue stick and glue the reflector tab on the specimen.

5) Add a dab of vacuum grease to your finger.



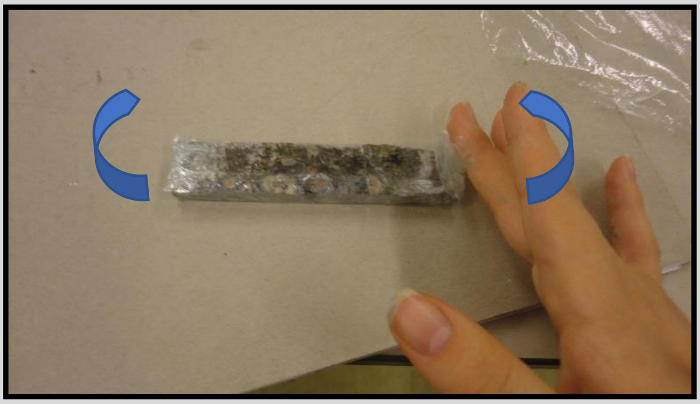
6) Smear the vacuum grease across the reflector tab.

7) Roll out some plastic wrap on the table. Place the specimen on the shrink wrap. The reflector tab should be facing down.

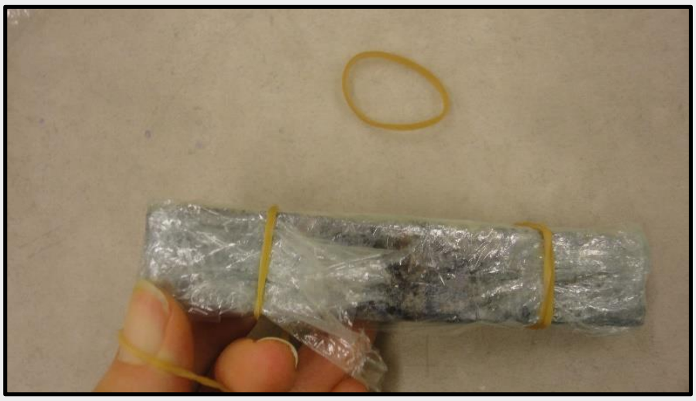
8) Fold the shrink wrap over the specimen.

9) Use a knife to cut out the specimen.

10) The specimen should look like this.



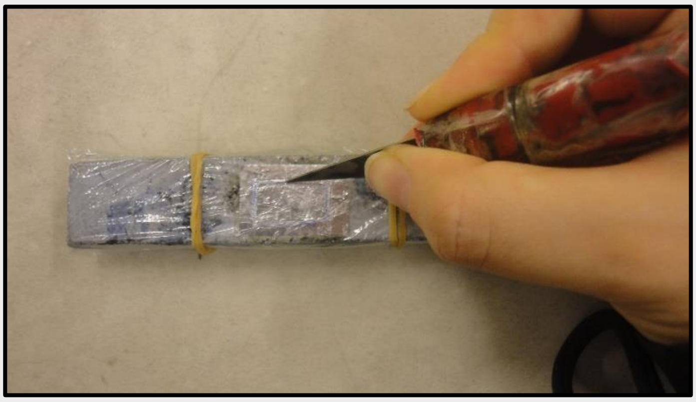
11) Smear some vacuum grease or glue (from a glue stick) to the unfolded shrink wrap. Then fold the excess shrink wrap behind the specimen

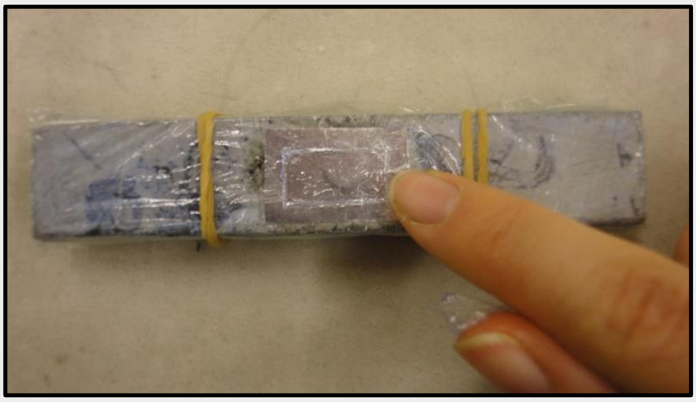


12) Strap two small rubber bands around the specimens to seal and hold the shrink wrap in place. Check that the rubber bands are placed within reasonable a distance away from the invar supports (in the freeze-warping box).

13) Turn the specimen around, with the reflector tab facing up.

14) On the shrink wrap, use a pen and draw a rectangle over the reflector tab.





15) Use a knife, and cut out the rectangular part of the shrink wrap.

16) The result should look like this.

A.2 FREEZE-WARPING BOX

A.2.1 THERMO COUPLES (TC)

There are five TCs used in the freeze-warping box. TCs are malleable wires, that can be bent into shape. They are attached to different parts of the freeze-warping box, and measure the following temperatures:

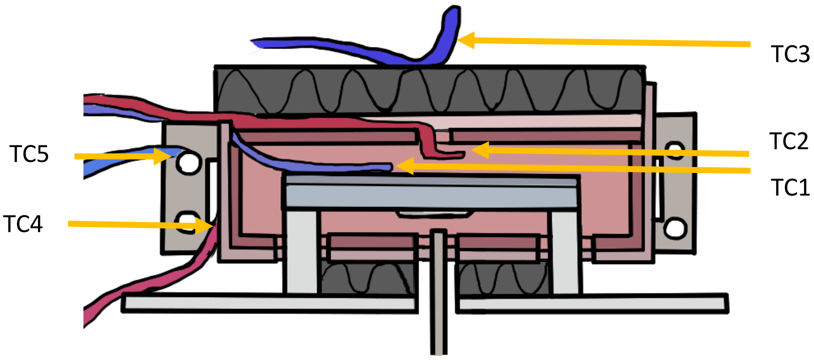
TC1 Above the specimen, $T_{specimen,above}$ [°C]

TC2 Air inside the freeze-warping box, $T_{air,inside}$ [°C]

TC3 Air outside the freeze-warping box, $T_{air,outside}$ [°C]

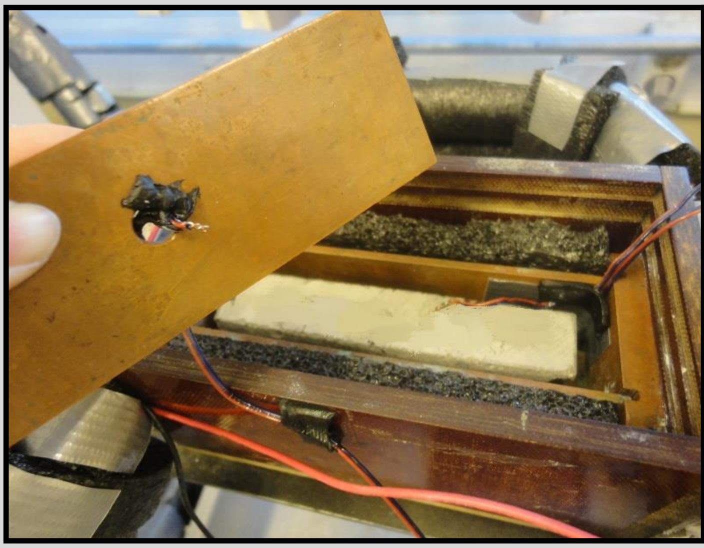
TC4 Cold side of the TEC, $T_{peltier,cold}$ [°C]

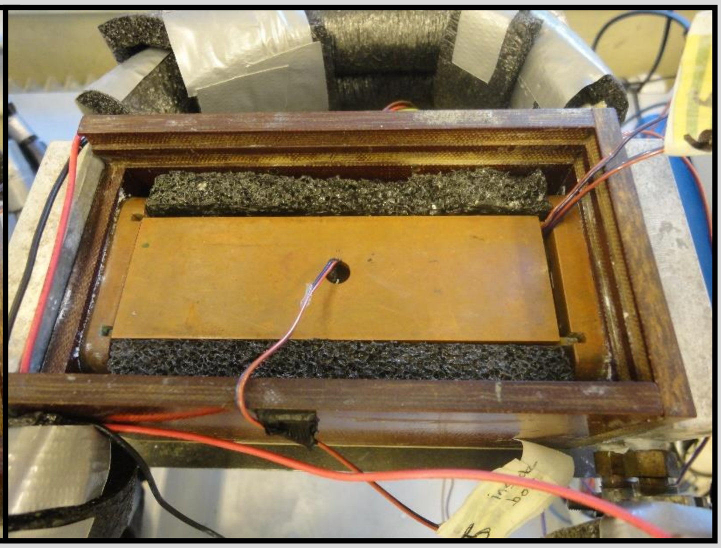
TC5 Liquid coming in through the cold water inlet, T_{inlet} [°C]



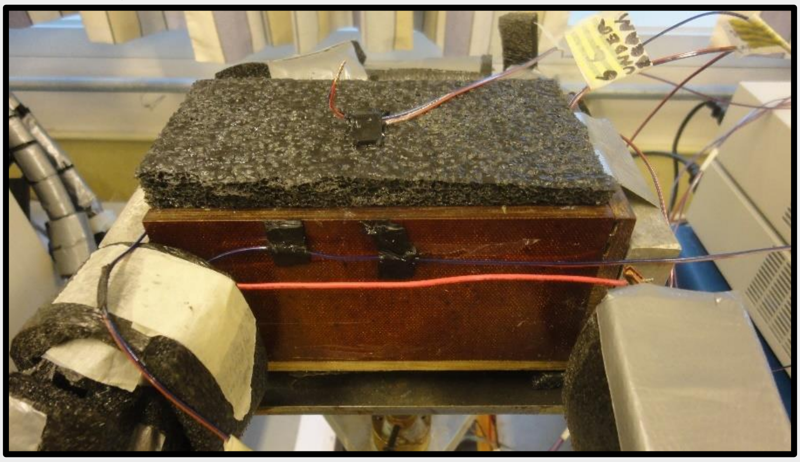
TC1 is taped inside the corner of the copper box. It is bent in such a way that it will lightly press onto the specimen. The TC measures the temperature above the specimen. $T_{specimen,above}$ [°C].

TC2 pokes through the hole in the copper lid, and is secured with butyl tape. It measures the temperature of the air inside the freeze-warping box, $T_{air,inside}$[°C].

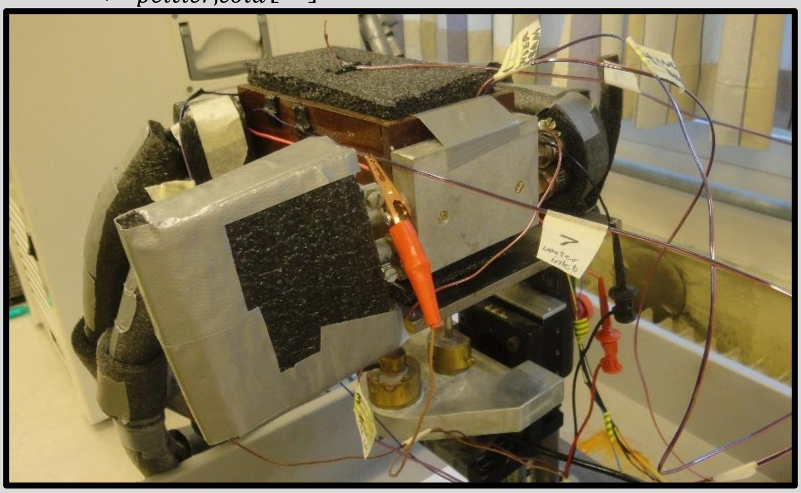




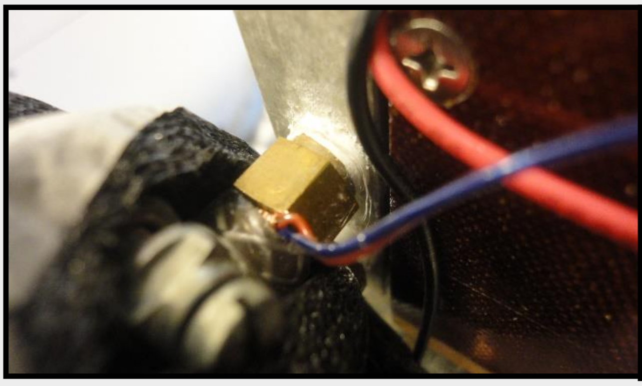
TC3 is secured on top of the insulation lid. It measures the temperature of the air outside the freeze-warping box. $T_{air,outside}$[°C]



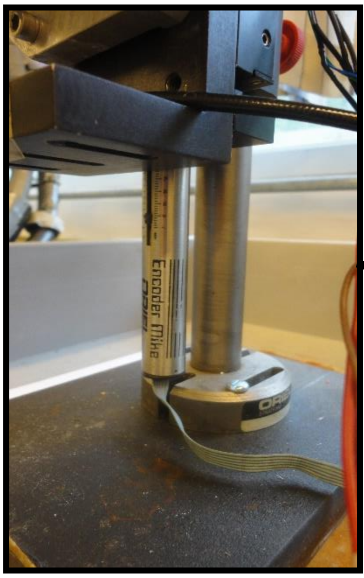
TC4 is carefully placed between the freeze-warping box, and the TEC, and held into place with an aluminum block screwed tightly onto the freeze-warping box. It measures the temperature of the Peltier’s cold side, $T_{peltier,cold}$[°C].

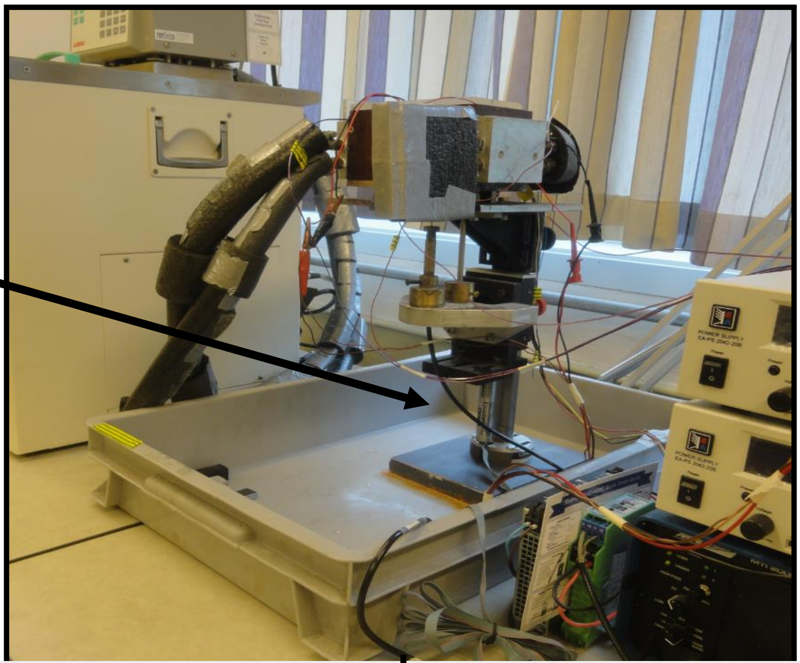


TC 6 measures the temperature of the cold liquid in the tubes, at the water inlet, T_{inlet}[°C]. The reason this temperature is measured is to check if the tubes are properly insulated. Ideally the TC should be placed inside tubes, in contact with the cool liquid. Since this is not possible, the second-best option is to place the TC on the metallic part of the tubes (with the highest thermal conductivity). Carefully poke it between the gap of the tube's metallic part, and the plastic tubes (as shown below). Carefully cover it with insulation.



A.2.2 STEP MOTOR





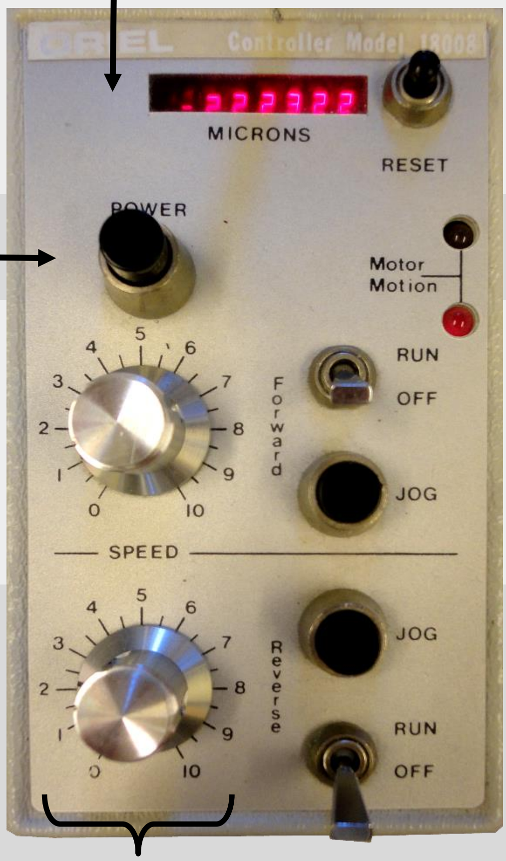
<u>Step motor remote</u>

The step motor is controlled by a step motor remote. The optic probe and the LVDT are placed on a platform. The step motor moves the platform up and down.

The “**POWER** ” button is the on/off switch.

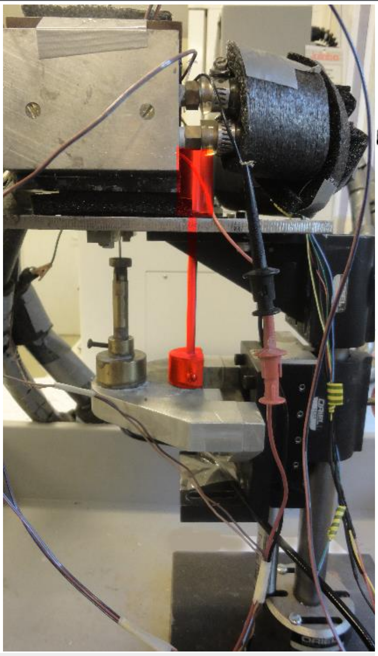
The upper row moves the platform up (towards the freeze-warping box). The “**RUN/OFF**” switch moves the platform automatically. The “**JOG**” button moves the platform manually.

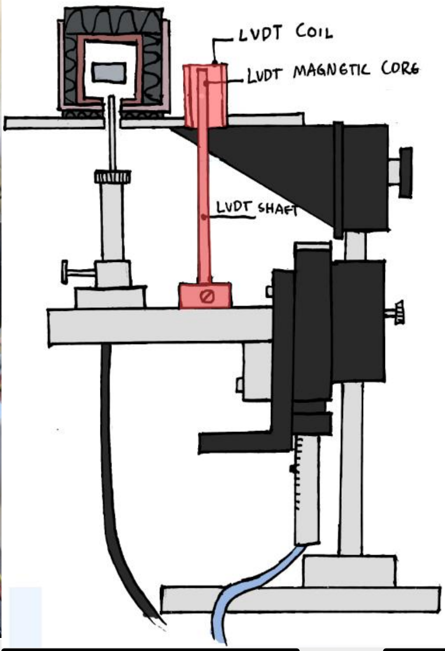
The lower row moves the platform down (away from the freeze-warping box). The “ **RUN/OFF** ” switch moves the platform automatically. The “ **JOG** ” button moves the platform manually.



Dials control the speed at which the step motor moves the platform.

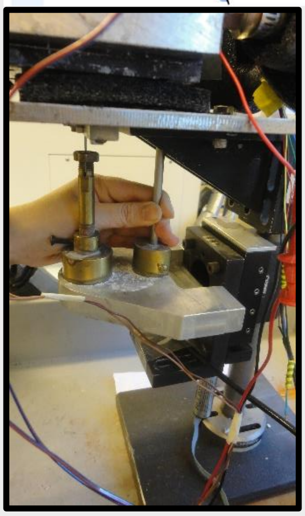
A.2.3 LVDT (LINEAR VARIABLE DIFFERENTIAL TRANSFORMER)



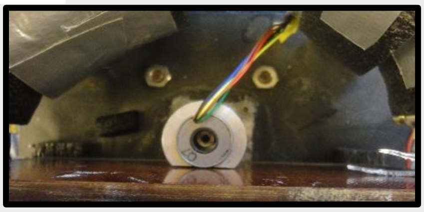


The photo on the left shows the freeze-warping box's set-up. The LVDT is colored in red.

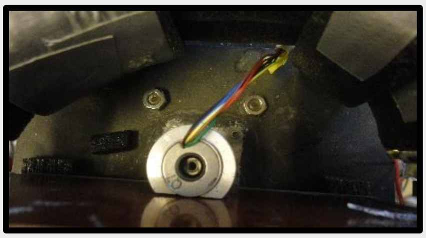
1) Use a screwdriver to loosen the LVDT shaft.



2) Use your hand to manually adjust the positioning of the LVDT shaft.

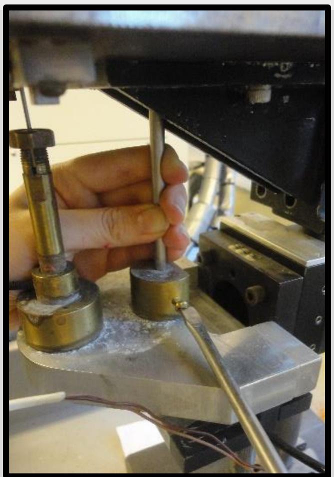


Here the LVDT shaft is touching the LVDT coil



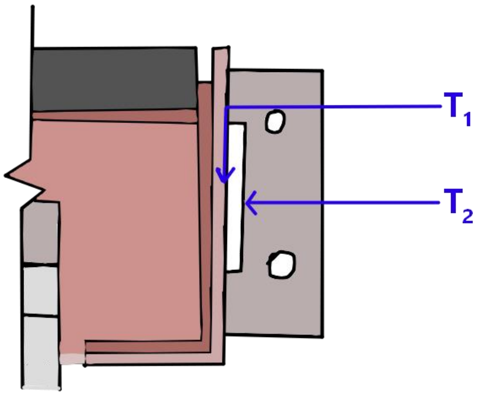
Here the LVDT shaft is not touching the LVDT coil.

3) Whiles your hand is adjusting the LVDT shaft, look at the LVDT coil from above. Make sure the LVDT shaft is not touching the LVDT coil.



4) Use a screwdriver to tighten the screw holding the LVDT in place

A.2.4 PELTIERS/THERMOELECTRIC COOL [A.1]

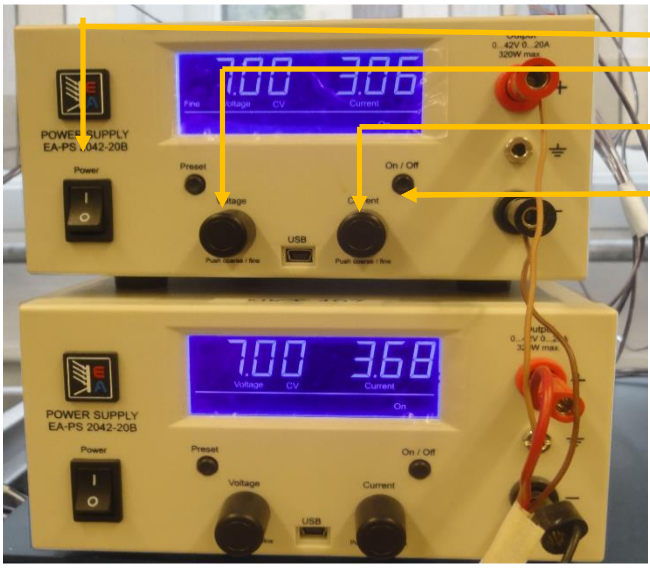


Two Peltiers are used to cool down the freeze-warping box. They are each connected to its own power supply. The power supply provides them with a voltage $\boldsymbol{V_{Peltier}}$**[V]** and current $\boldsymbol{I_{Peltier}}$ [amps]. The temperature difference across the TEC is given as:

$$\Delta T_{Peltier} = T_{Peltier,hot} - T_{Peltier,cold}$$

$\Delta T_{Peltier}$ can be regulated by $V_{Peltier}$[V]. The temperature on hot side of the Peltier, $T_{Peltier,hot}$ can be regulated by the temperature in Julabo, T_{Julabo}

Each Peltier is connected to its own **power supply.** The power supply regulates the voltage $V_{Peltier}$[V].



This the on//off switch for the power supply

This dial regulates the voltage.

This dial regulates the current

This is the on/off switch that provides a voltage to the TEC.

The equation below shows the relation between the temperature of the specimen $T_{specimen,aboce}$[°C], and the voltage of the Peltiers $V_{Peltier}$[V].

$$T_{specimen,above} = \begin{cases} -3.0822V_{Peltier} - 19.984 & for\ T_{Julabo} = 20[°C] \\ -2.47347V_{Peltier} - 4.317 & for\ T_{Julabo} = -12.50[°C] \end{cases}$$

NOTE

The equation above applies for an invar steel specimen. If a different specimen is used, the specimen’s temperature $T_{specimen,above}$may differ slightly.

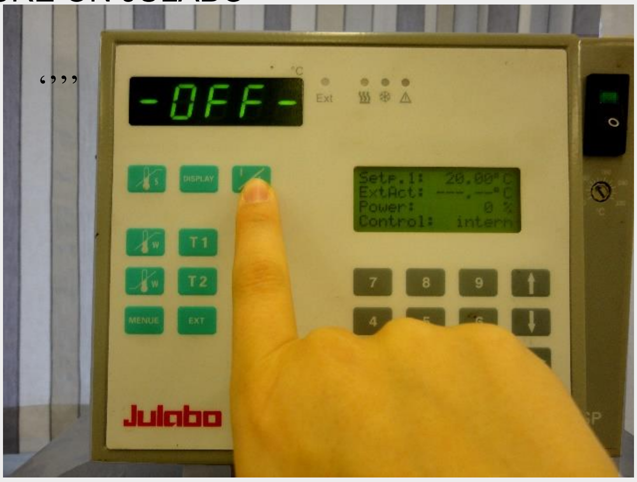
A.2.5 REFRIGERATED/HEATING CIRCULATOR (JULABO)[A.2]

The refrigerated/heating circulator (further called Julabo) pumps cooling liquid (water/ethanol mixture) via tubes around the Peltiers. This liquid removes excess heat from the Peltiers' hot side.

The left figure points to the box that programs Julabo's temperature $\boldsymbol{T_{Julabo}}$.

HOW TO SET A CONSTANT TEMPURATURE ON JULABO

1) Switch on the power supply for Julabo



2) Switch on Julabo.

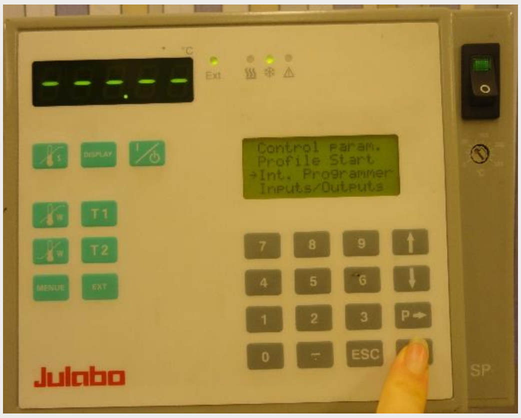
3) Type in the desired temperature, then press ↵

HOW TO PROGRAM A TEMPERATURE CYCLE ON JULABO

The following example shows how to program the temperature cycle below:

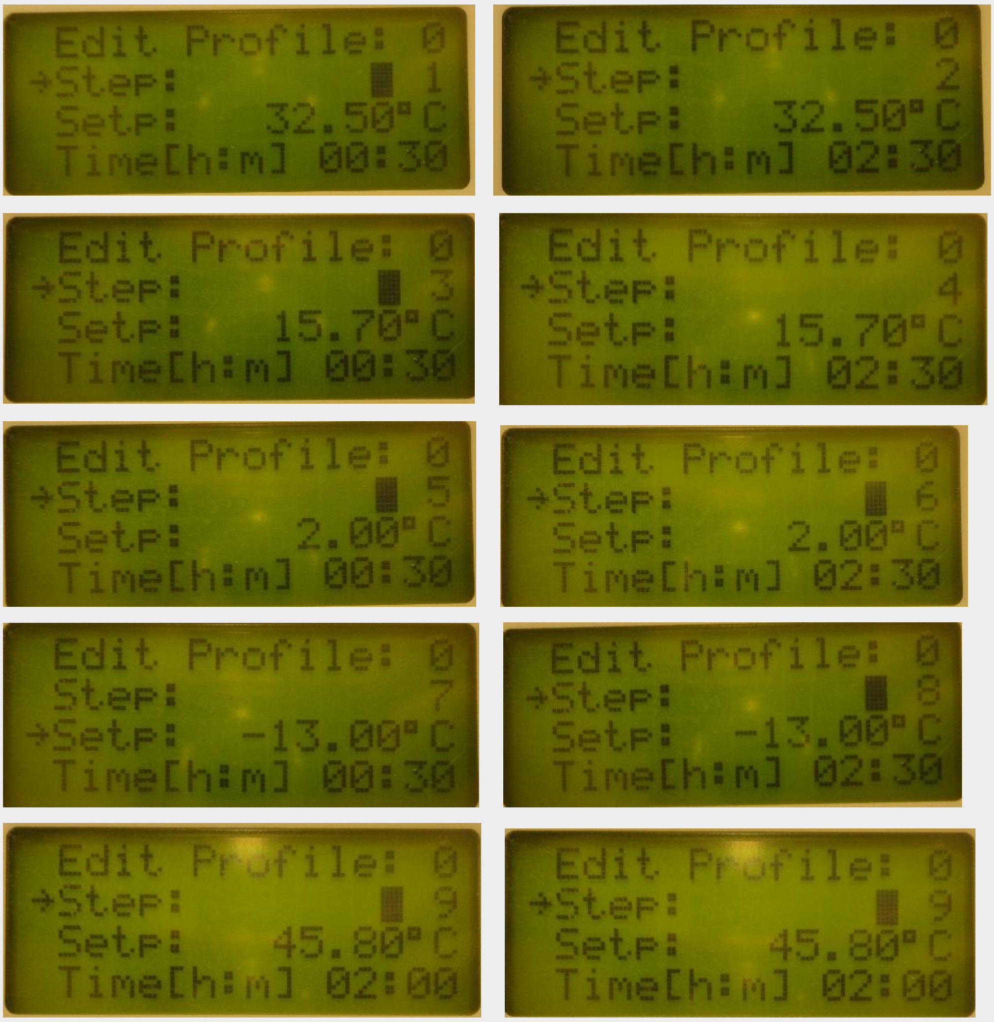
	Time, Δt,[h]	**Accumulated time, t, [h]**	**Target temperature for the specimen, $T_{Specimen,target}$ [°C]**	**Julabo, T_{Julabo}, [°C]**	**Peltier, $V_{Peltier}$, [V]**	**Description of temperature change**
Step 0	01:00	01:00	20	45.8	5.70	Constant
Step 1	00:30	01:30	10	32.5	5.70	Decrease
Step 2	02:30	4:00	10	32.5	5.70	Constant
Step 3	00:30	4:30	0	15.7	5.70	Decrease
Step 4	02:30	7:00	0	15.7	5.70	Constant
Step 5	00:30	7:30	-10	2.0	5.70	Decrease
Step 6	02:30	10:00	-10	2.0	5.70	Constant
Step 7	00:30	10:30	-20	-13.0	5.70	Decrease
Step 8	02:30	13:00	-20	-13.0	5.70	Constant
Step 9	02:00	15:00	20	45.8	5.70	Increase
Step 10	08:00	23:00	20	45.8	5.70	Constant

1) Press “MENU”, then use the arrow buttons to navigate to “Int. Programmer”. Then press ↵



2) Edit profile: 0. Use the up and down arrows to navigate.
Type in “Setp:” 45.00, and “Time[h:m]:” 01:00.

3) Program the following time and temperatures for the **steps** shown below:



The temperature of the specimen is described in the equation below:

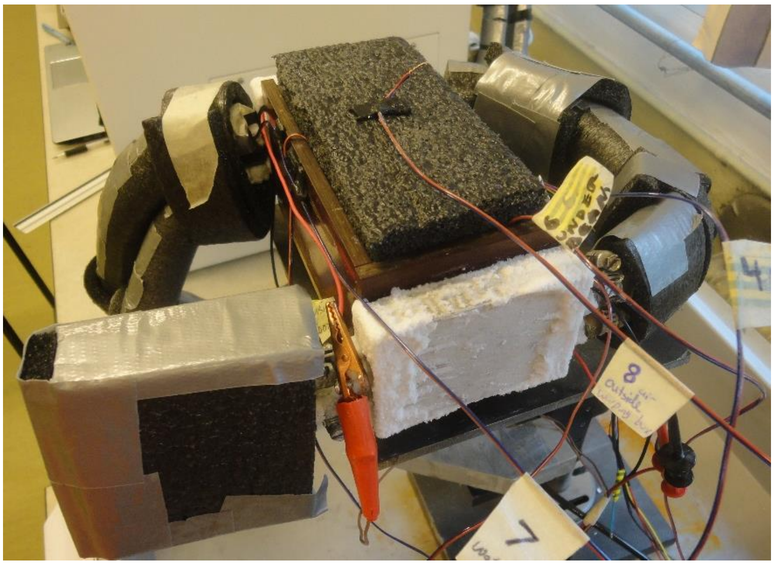
$$T_{specimen,above} = \begin{cases} -0.706T_{Julabo} - 6.4832 & for\ V_{Peltier} = 5.70[V] \\ -0.6433T_{Julabo} - 10.964 & for\ V_{Peltier} = -0.00[V] \end{cases}$$

Julabo has a lower temperature limit of: $T_{Julabo} \geq -22[°C]$

NOTE

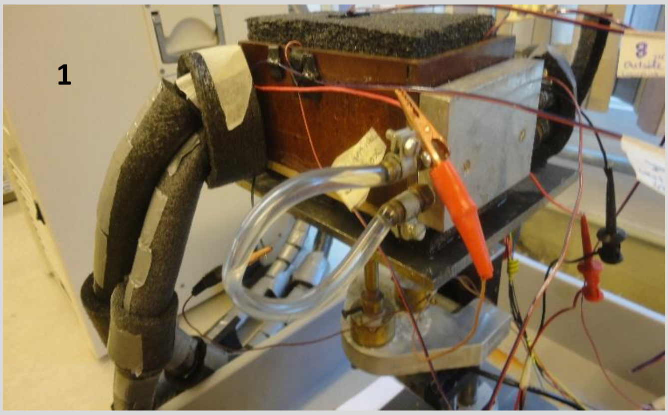
The equation above applies for an invar steel specimen. If a different specimen is used, the specimen's temperature $T_{specimen,above}$ may differ slightly.

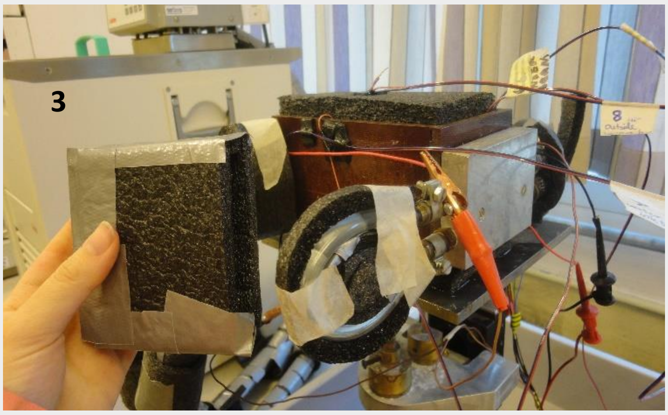
A.2.6 FOAM INSULATION AROUND THE TUBES

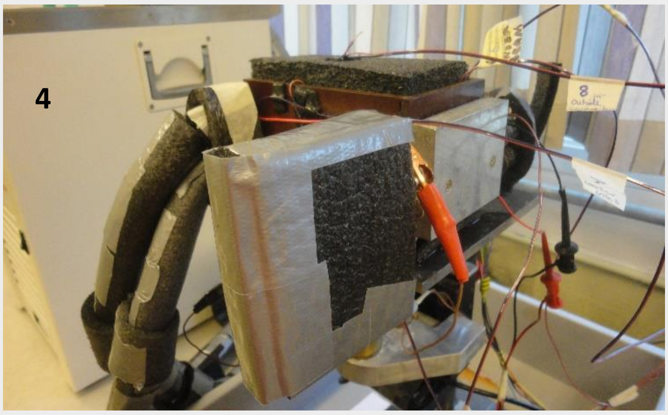


Foam insulation covers most of the tubes. It is held together with duct tape. Insulation is taped around the tubes as shown in the photos.

For the bending tubes, the following steps were made to insulate it:







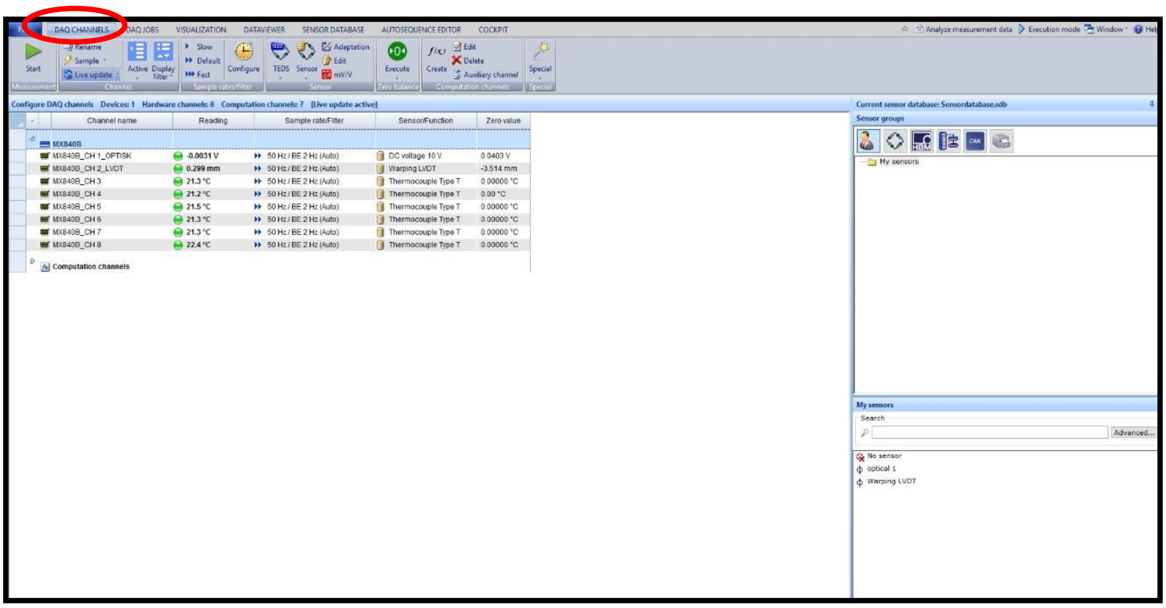
A.2.7 QUANTUM X

The photo to the left shows Quantum X. It continuously logs the measurements made by five TCs, one fotonic sensor/optic probe, and one LVDT. Quantum X transfers this logged data to the PC program called catman®Easy.

A.2.8 CATMAN®EASY

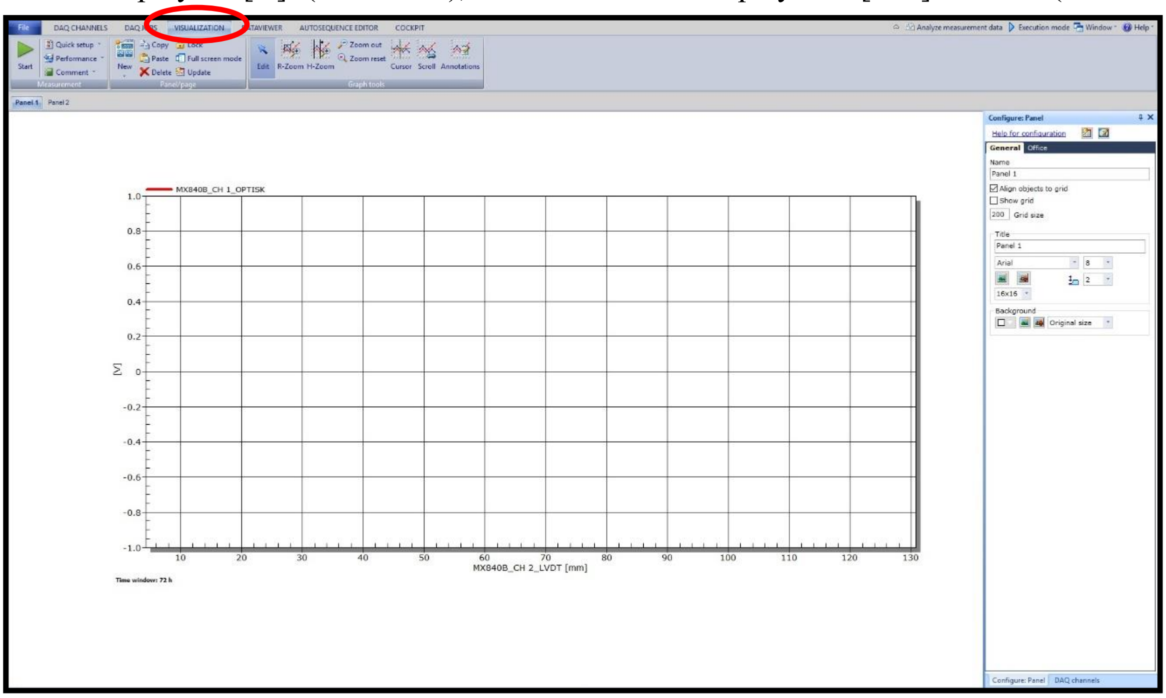
On catman®Easy, the tab “DAQ channels” shows all the measuring devices connected to Quantum X. Each measuring device is on its own “channel”:

- Channel 1: Optic probe, measures reflected light, I [V]
- Channel 2: LVDT, measures displacement, d [mm]
- Channel 3: TC4, cold side of the Peltier, $T_{peltier\ cold}$ [°C]
- Channel 4: TC1, temperature over the specimen, $T_{specimen,above}$ [°C]
- Channel 5: TC2, air inside the freeze-warping box, $T_{air,inside}$ [°C]
- Channel 6: is not in use
- Channel 7: TC5, water inlet, T_{inlet} [°C]
- Channel 8: TC3, air outside the freeze-warping box, $T_{air,outside}$ [°C]

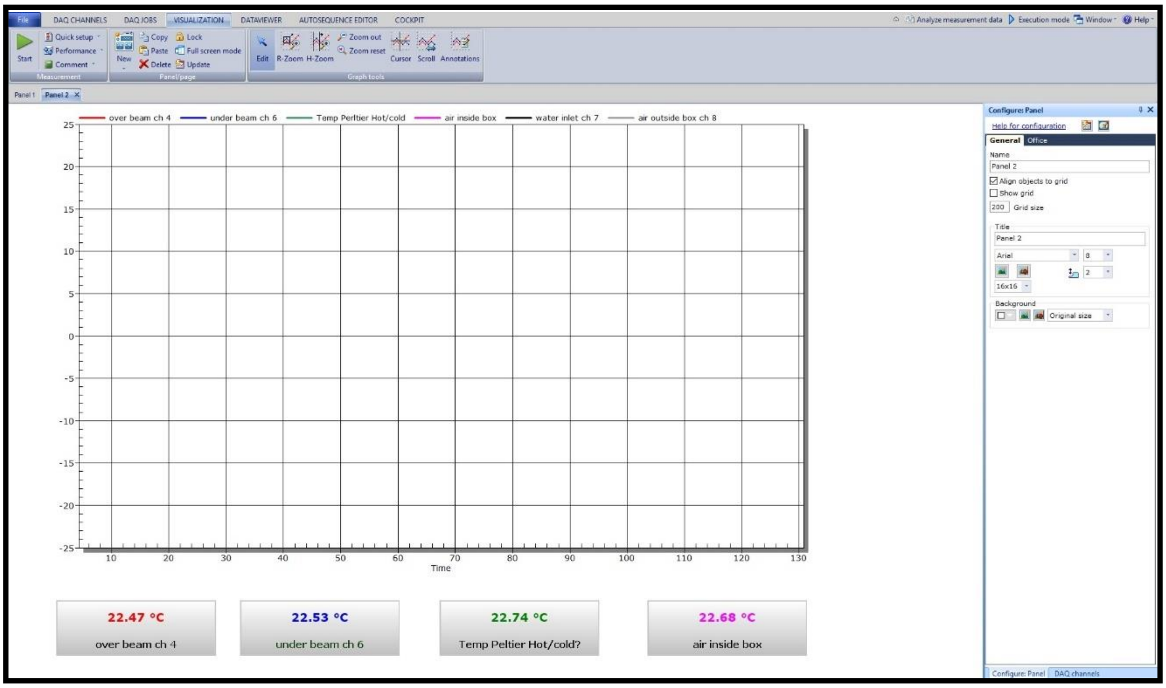


The tab “Visualization” has two “panels”.

- **Panel 1** plots the Calibration Curve during the *calibration procedure*. The y-axis displays I [V] (channel 1), and the x-axis displays d [mm] LVDT (channel 2).



- **Panel 2** will plot the temperature-time curve during a *temperature cycle*. The x-axis displays the time t [h], the y-axis plots the temperatures $T_{peltier\ cold}$[°C], $T_{specimen,over}$[°C], $T_{air,inside}$[°C], T_{inlet}[°C], and $T_{air,outside}$[°C]



A.3 CALIBRATION PROCEDURES [A.3] [A.4]

NOTICE!

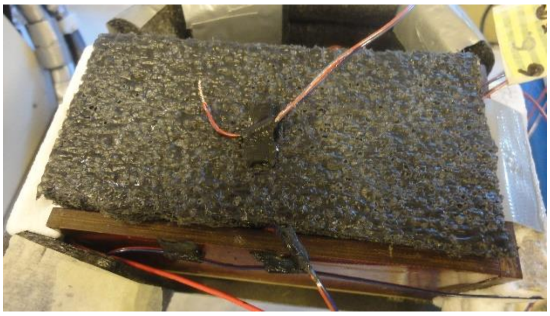
1. The optic probe/fotonic sensor must be re-calibrated whenever:
   - There is a new specimen in the freeze-warping box
   - The specimen moves
   - The optic probe touches the specimen
   - There is a new temperature cycle experiment
2. THE OPTIC PROBE MUST NEVER TOUCH THE SPECIMEN! Here are the reasons:
   - The specimen's reflector tab is covered with grease, and might cover the optic probe's head.
   - The optic probe may accidentally move the specimen.
3. If the optic probe touches the specimen, clean the optic probe's head with cloth lightly soaked with ethanol.

CALIBRATING THE FOTONIC SENSOR

1) Open the lid of the freeze-warping box, and place an object with a straight edge on top of the invar supports. (The photo below shows an invar specimen used as a straight edge.) Use the step motor and position the optic probe close to the straight edge. There should be a 1 - 2 [mm] gap between the optic probe and the straight edge.

2) Remove the straight edge, and place a specimen on the invar supports. The reflector tab should be facing down towards the optic probe.

3) Put on the lids.



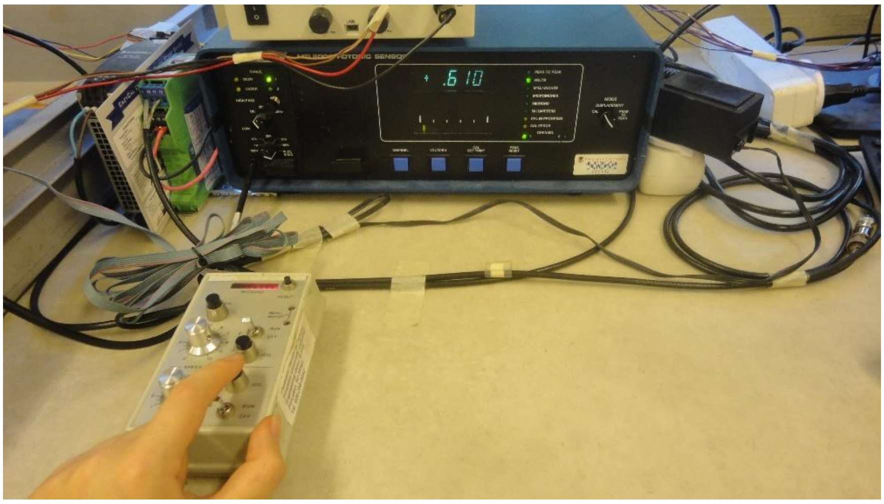
4) Turn on the fotonic sensor.

Turn on Julabo and set it to T_{Julabo} = 45.80 [°C]. Turn on the Peltier/TEC and set both of its power supplies to 5.70 [V].

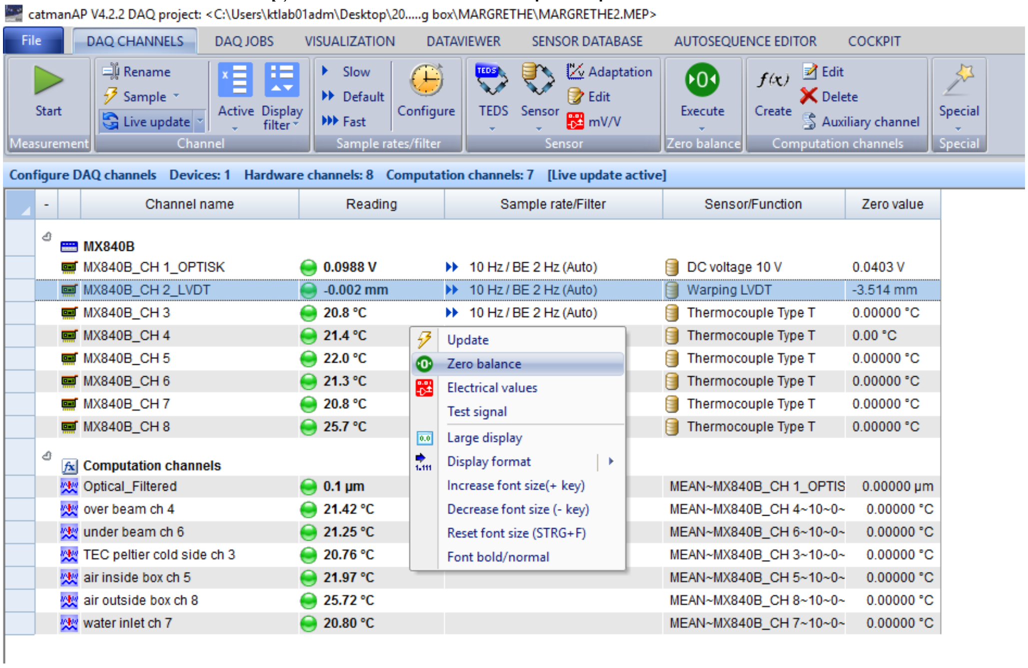
Wait 1 hour, until the specimen's temperature has set to $T_{specimen,above}$ =20 [°C].

5) On the fotonic sensor, set the "MODE to "CAL".

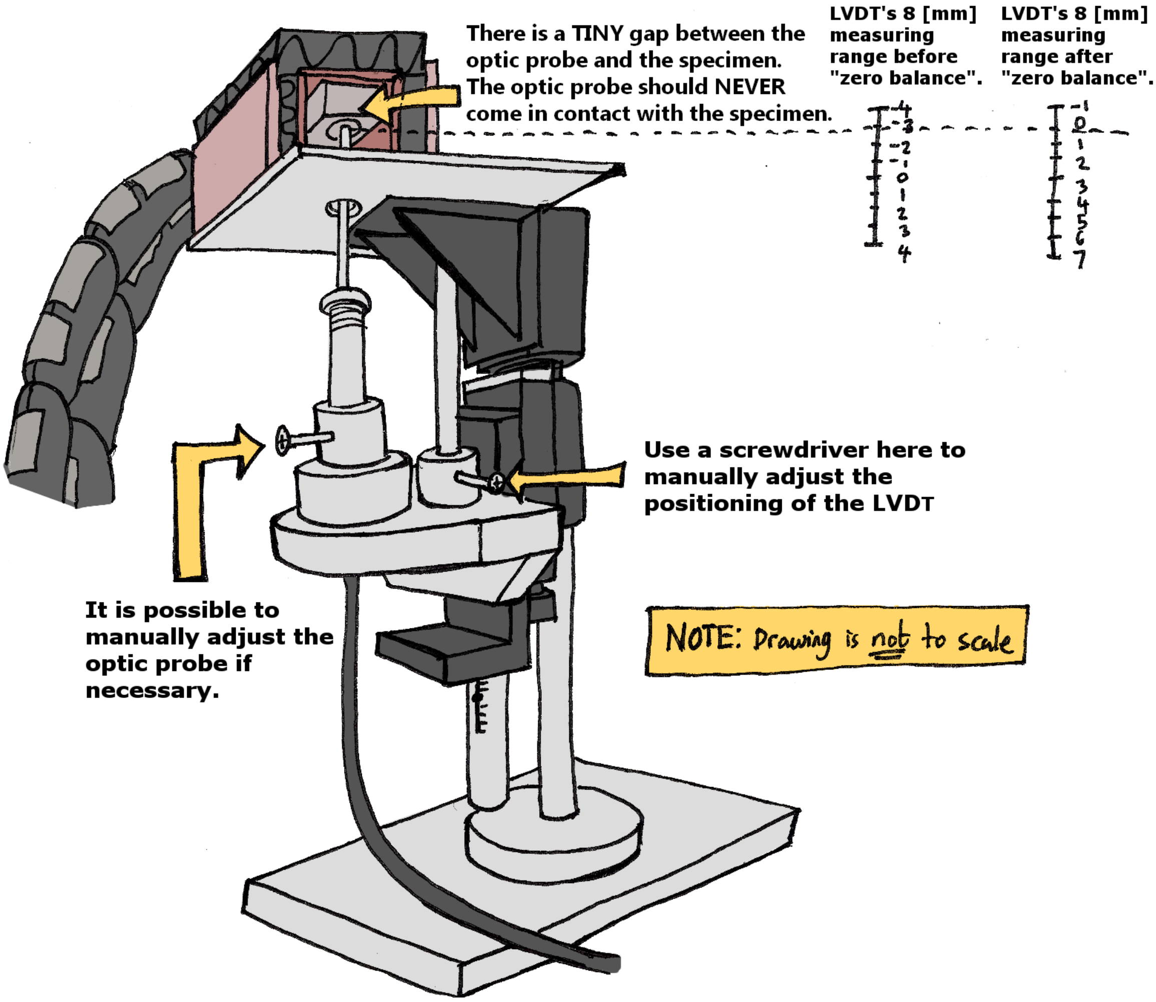
6) Use the step motor to slowly move the optic probe as close to the specimen's surface. The fotonic sensor should show a reading between 0.050 – 0.100 [V].



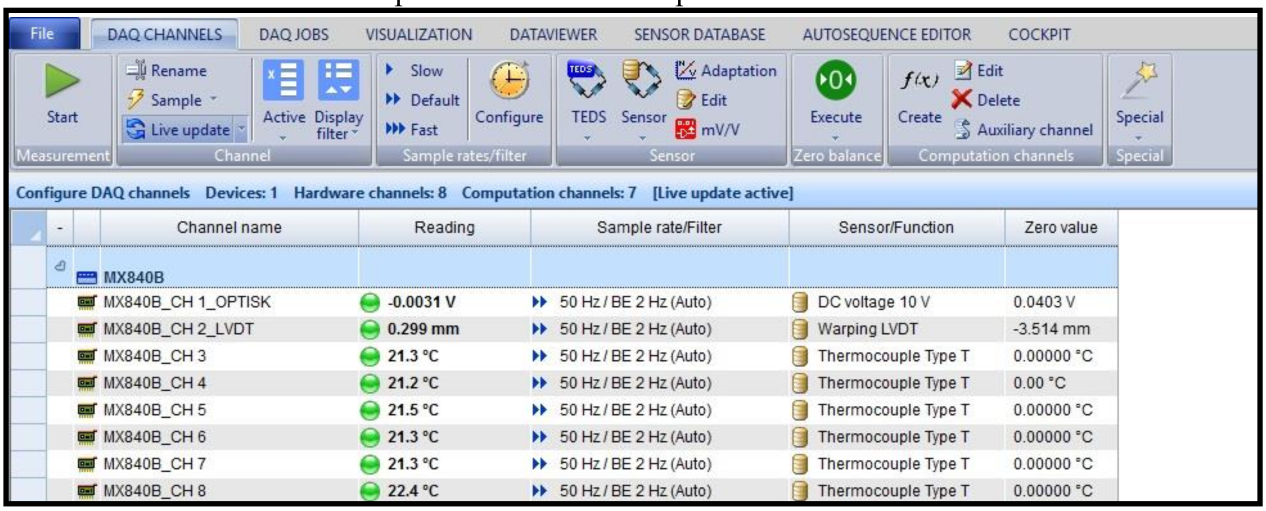
7) Look at the program catman®Easy, and look at the measured displacement of the LVDT. It should show a reading between -4 and -3 [mm].



If it does not, then manually adjust the LVDT until catman®Easy shows a reading between -4 and -3 [mm]. Then set the LVDT's channel to "Zero balance".

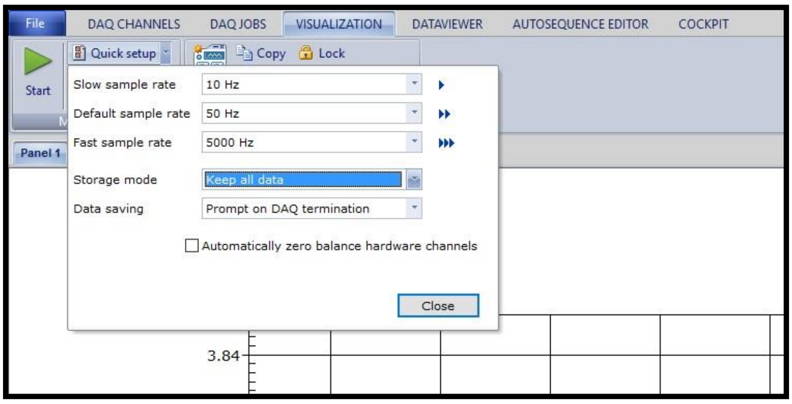


8) On catman®Easy, go to “DAQ CHANNELS”. For all eight channels, set the “Sample rate/Filter” to “default sample rate”. Default sample rate is marked with this icon: ⏩

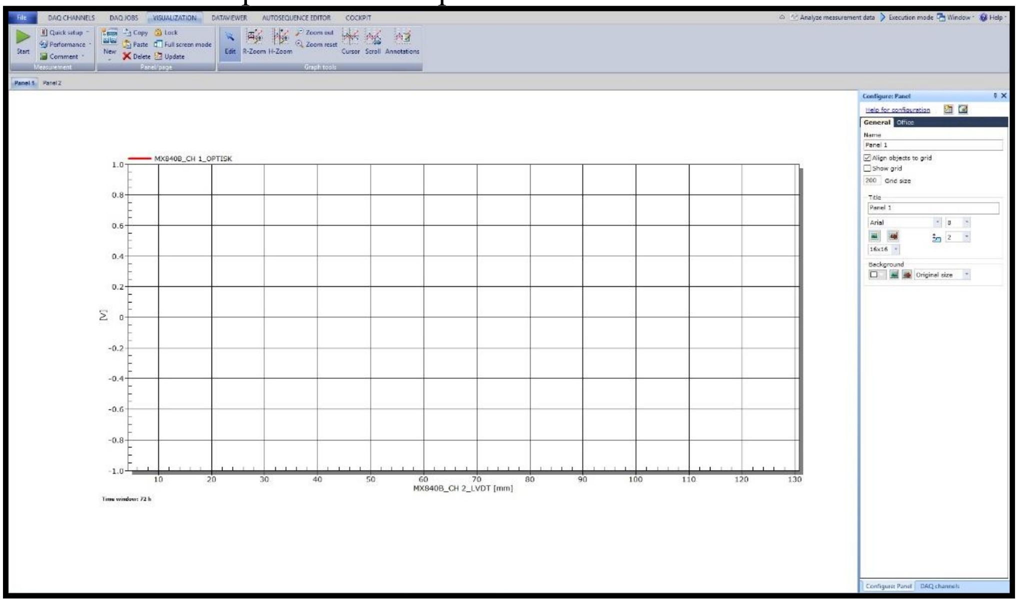


Channel name	Reading	Sample rate/Filter	Sensor/Function	Zero value
MX840B				
MX840B_CH 1_OPTISK	-0.0031 V	50 Hz / BE 2 Hz (Auto)	DC voltage 10 V	0.0403 V
MX840B_CH 2_LVDT	0.299 mm	50 Hz / BE 2 Hz (Auto)	Warping LVDT	-3.514 mm
MX840B_CH 3	21.3 °C	50 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 4	21.2 °C	50 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00 °C
MX840B_CH 5	21.5 °C	50 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 6	21.3 °C	50 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 7	21.3 °C	50 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C
MX840B_CH 8	22.4 °C	50 Hz / BE 2 Hz (Auto)	Thermocouple Type T	0.00000 °C

9) Go to VISUALIZATION. Click on “Quick setup”. Set the Default sample rate to “50 Hz”. Set the storage mode to “keep all data”:

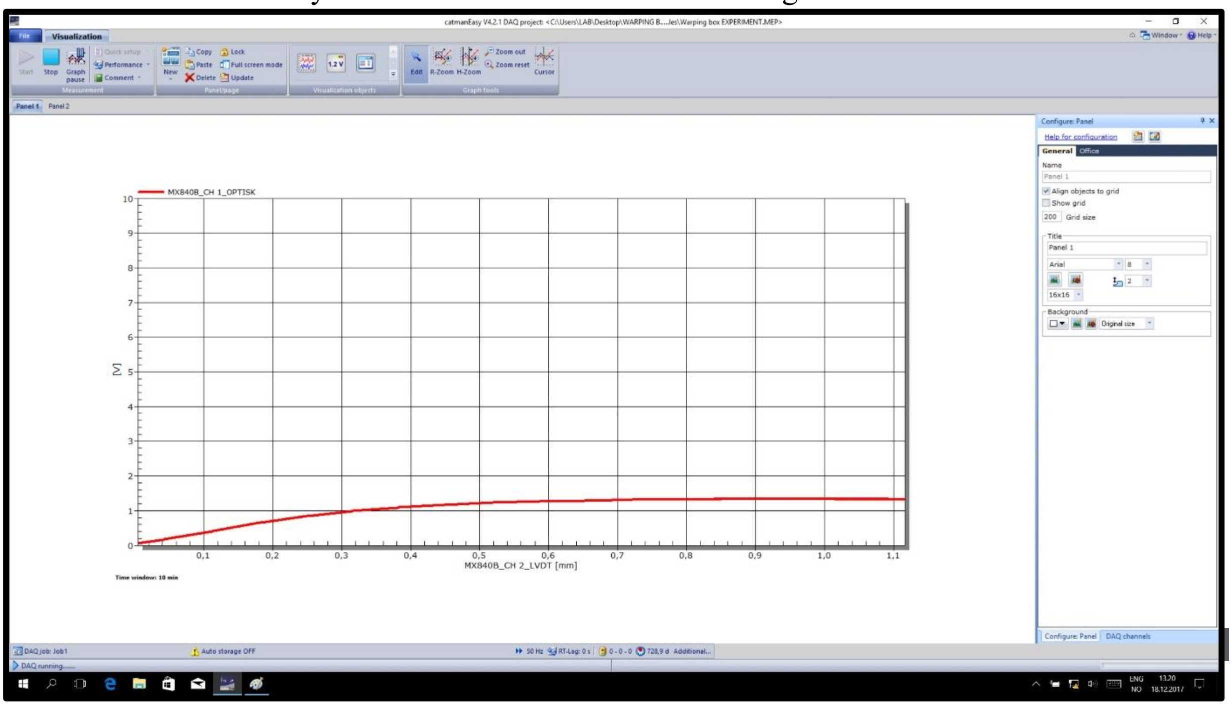


10) Make sure Panel 1 is open on the computer screen.

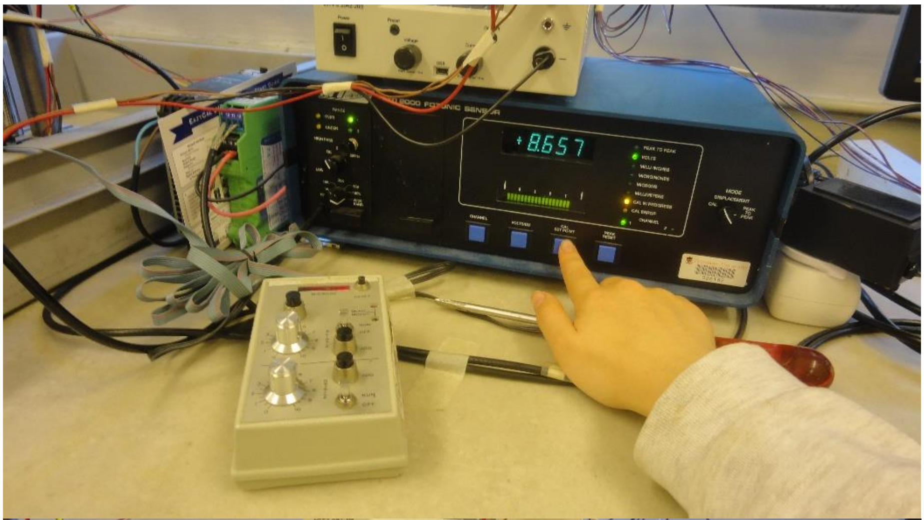


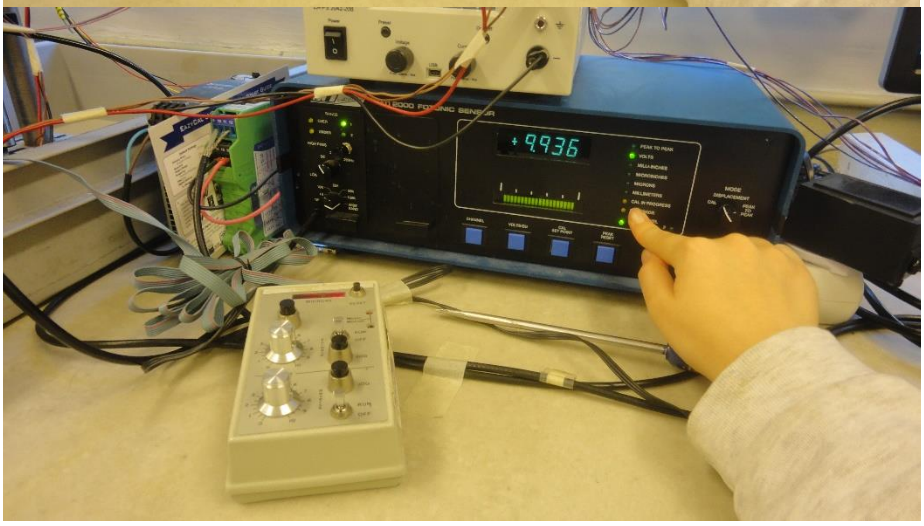
11) Press “Start” 

12) Use the step motor to slowly move the optic probe away from the specimen. Stop once Panel 1 shows that you have reached a maximum reading.

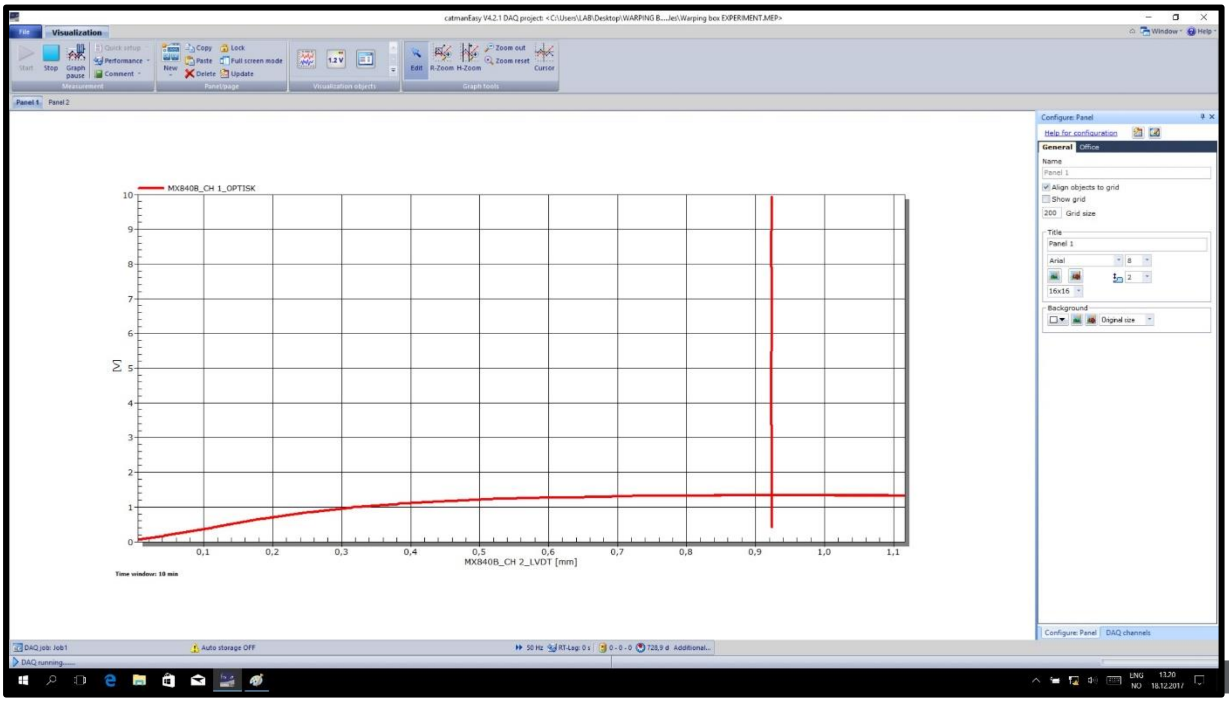


13) On the fotonic sensor, press the button “CAL SET”. This button will adjust the lighting in the optic probe so that the reading at the **optic peak** will show 10.000 ± 0.075 [V]. The “Calibration in progress” lightbulb will glow. Wait until this lightbulb turns off. Now the optic probe is calibrated.

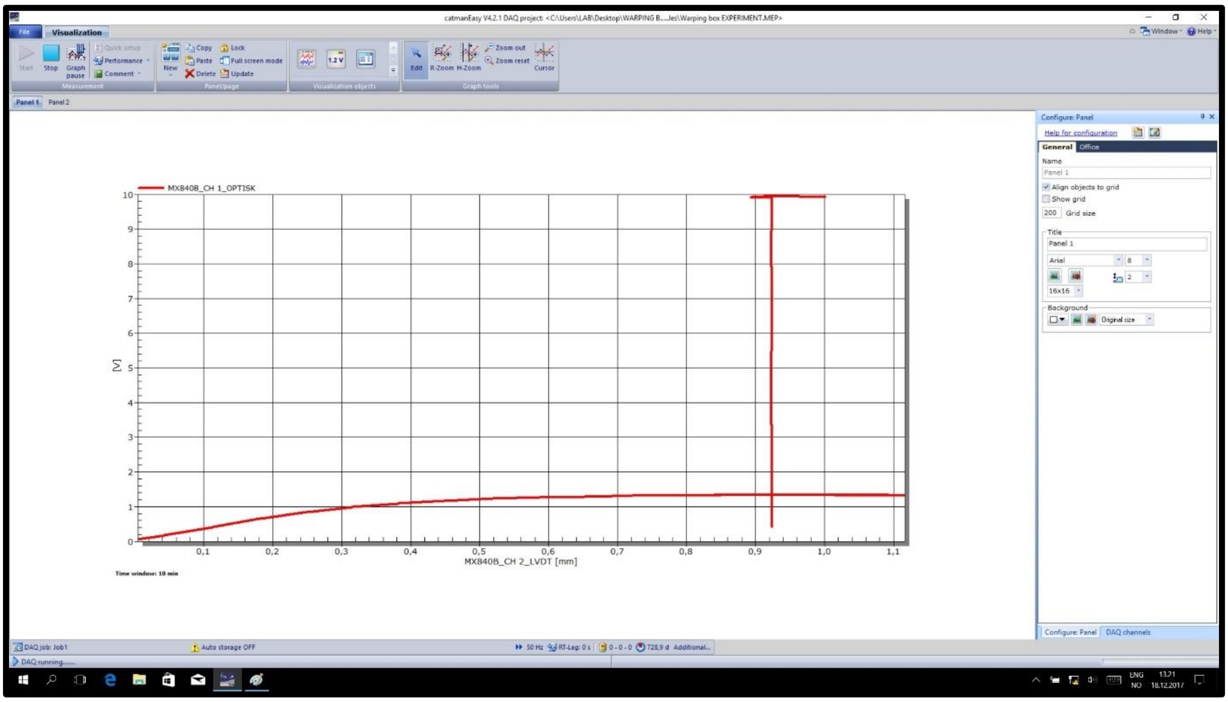




Panel 1 should show a graph like the one below.

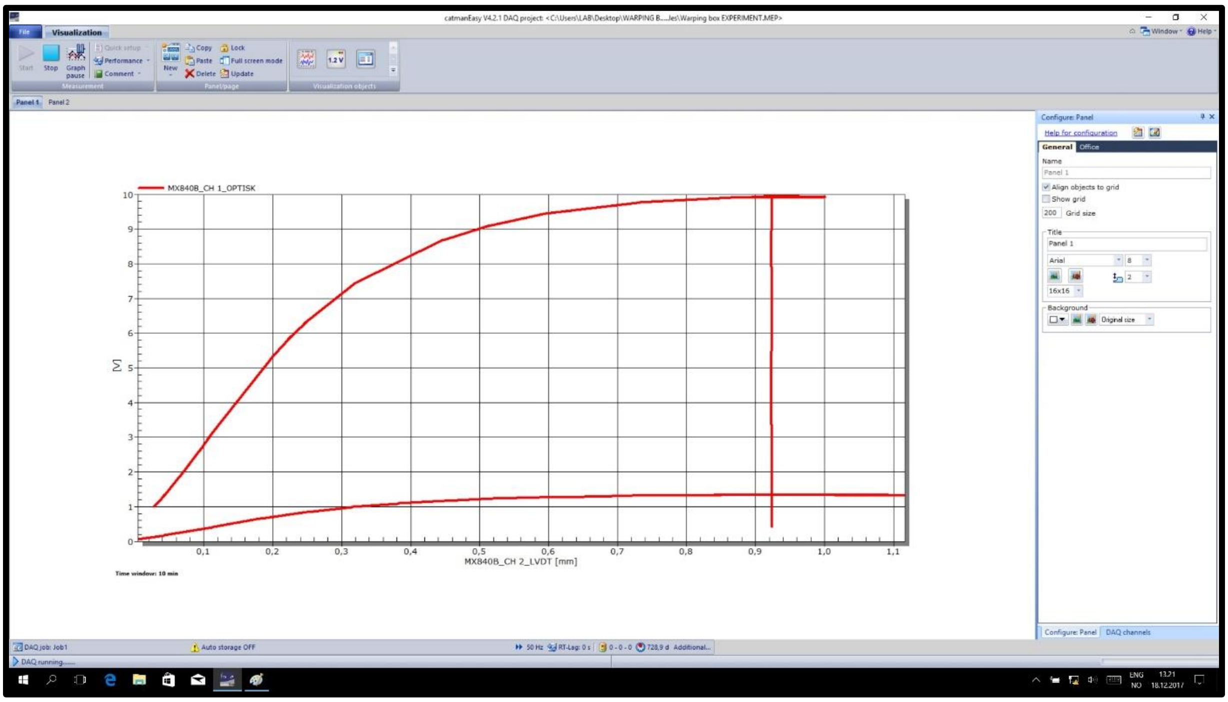


14) Use the step motor, and move the optic probe a bit up and down. This is done to make sure that you have found the optic peak.



15) On the fotonic sensor, set the mode to "DISPLACEMENT". If the lightbulb besides "MICRONS" light up, press the button "VOLTS/EU", The screen should now show a reading in volts again.

16) Move the optic probe away from the freeze-warping box until the fotonic sensor shows a reading of $V_{optic} \approx 1.000$ [V].

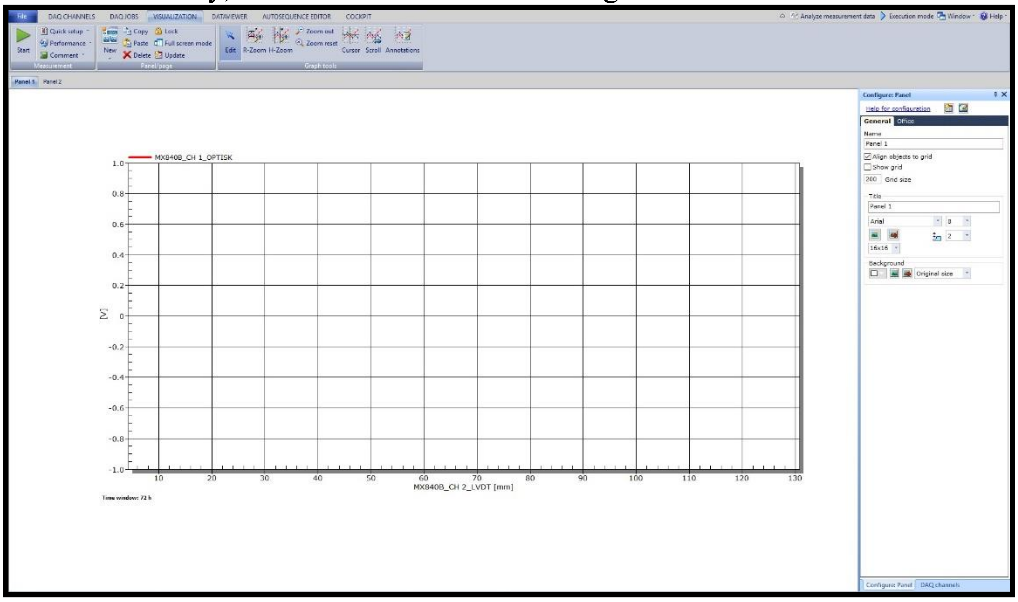


17) Then press the blue “Stop” button. Do not save anything.

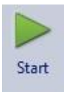
The fotonic sensor and the optic probe is now calibrated.

FIINDING THE CALIBRATION CURVE

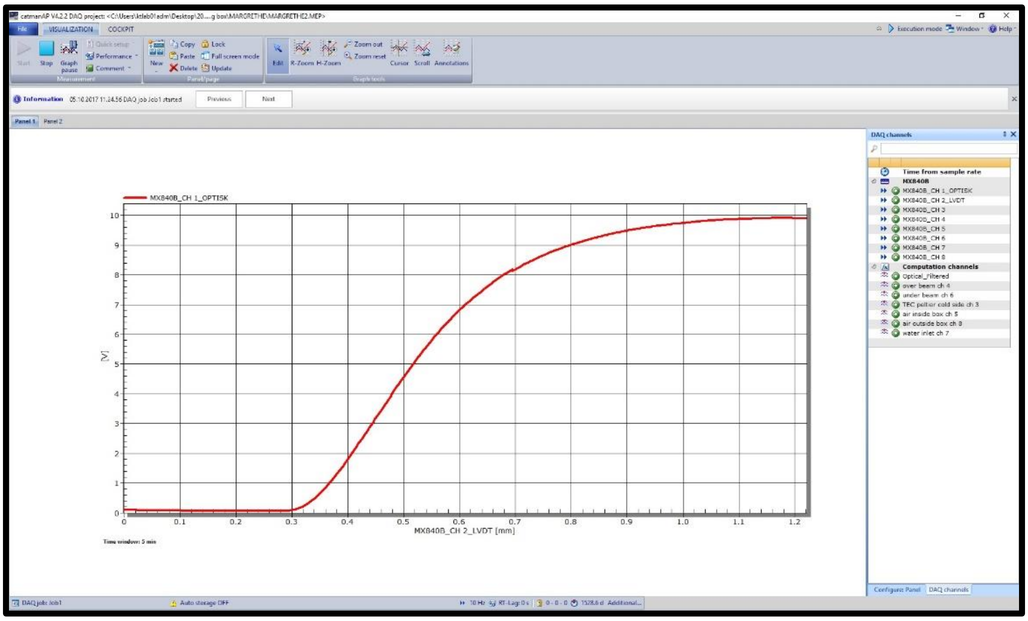
18) On catman®Easy, make sure Panel 1 is showing on the PC's screen.



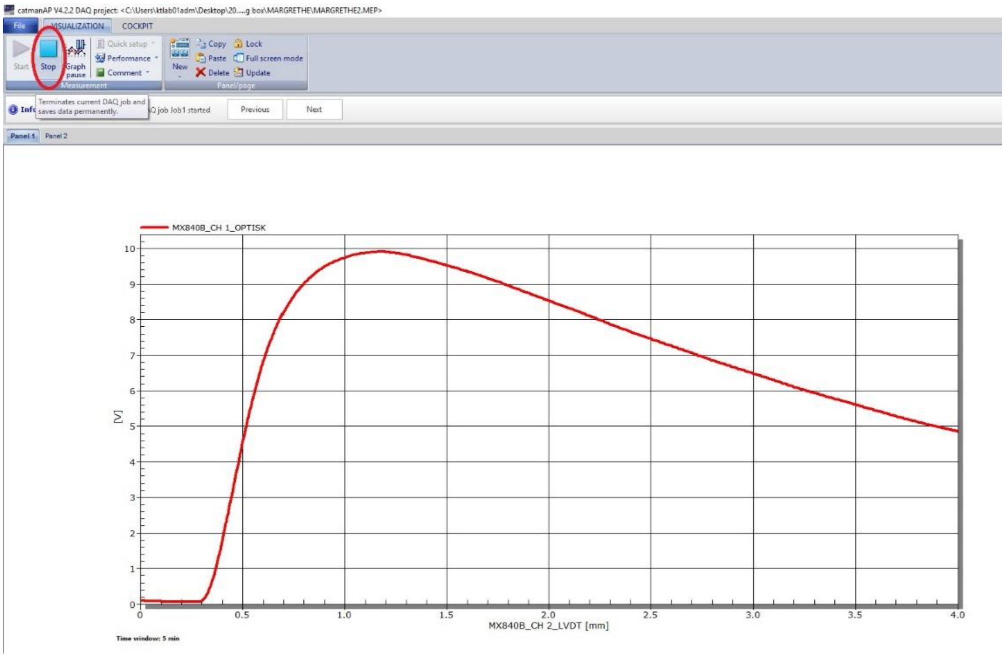
19) Press "Start"



20) Use the step motor to <u>slowly</u> move the optic probe away from the specimen's surface. Follow along the logged values on "Panel 1". Continue to move the optic probe until it reaches its optic peak (maximum reading on fotonic sensor). "Panel 1" should look like this:

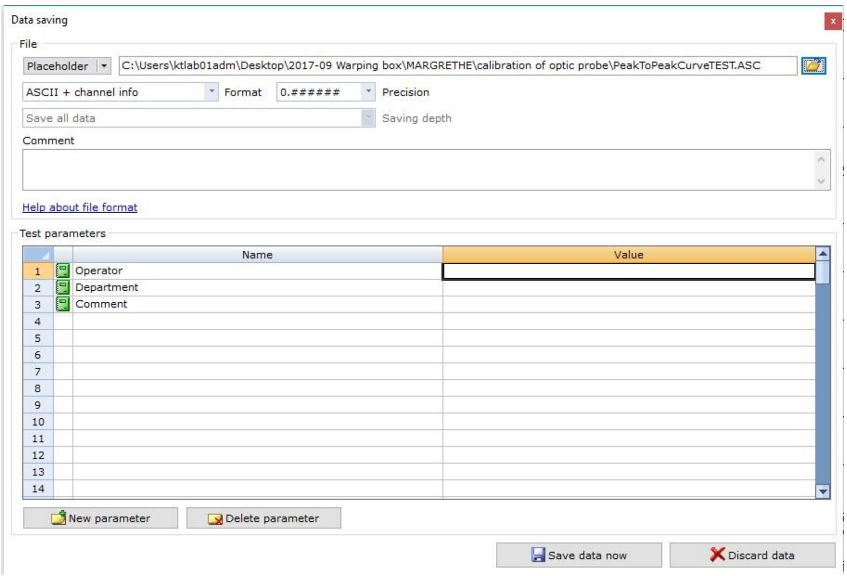


21) Continue to use the step motor, and slowly move the optic probe away from the specimen's surface until the LVDT's reading shows about 4 [mm]. "Panel 1" should look like this:



22) Press “STOP”.

Name the file Calibration Curve, then save the data as an ASC II file.

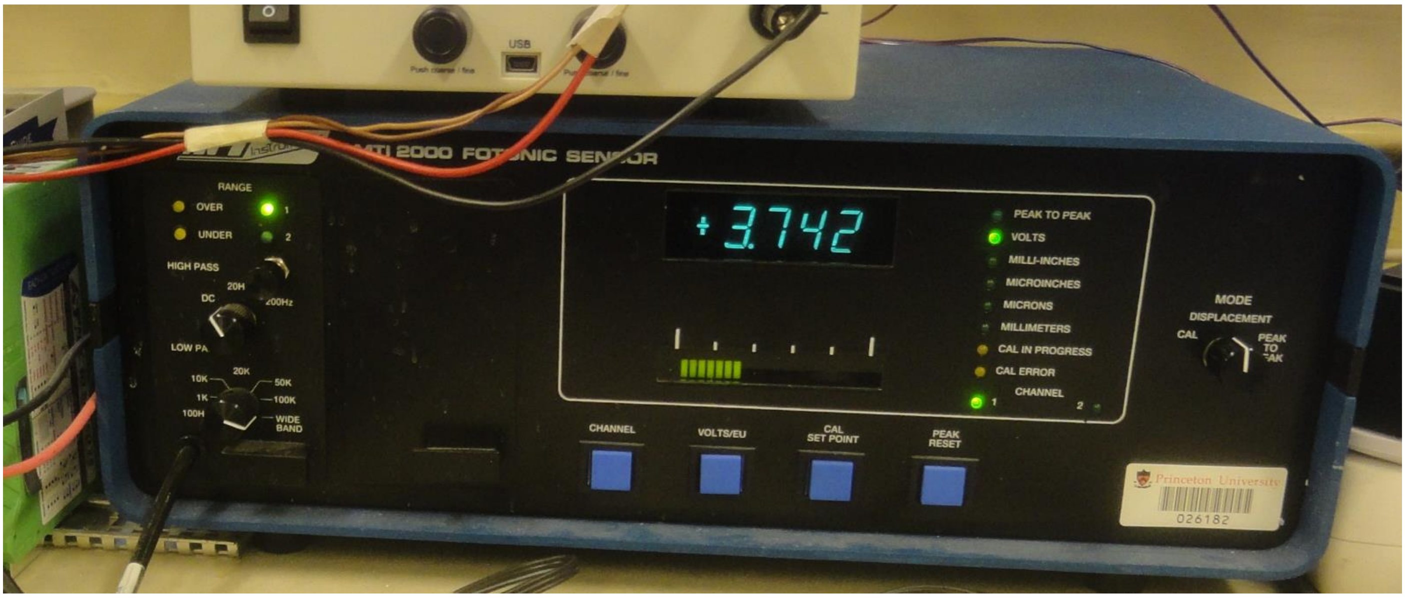


A.4 FREEZE-WARPING BOX EXPERIMENT

1) After the calibrations procedure is completed, use the step motor to position the optic probe in the middle of “Range 1” OR “Range 2”.

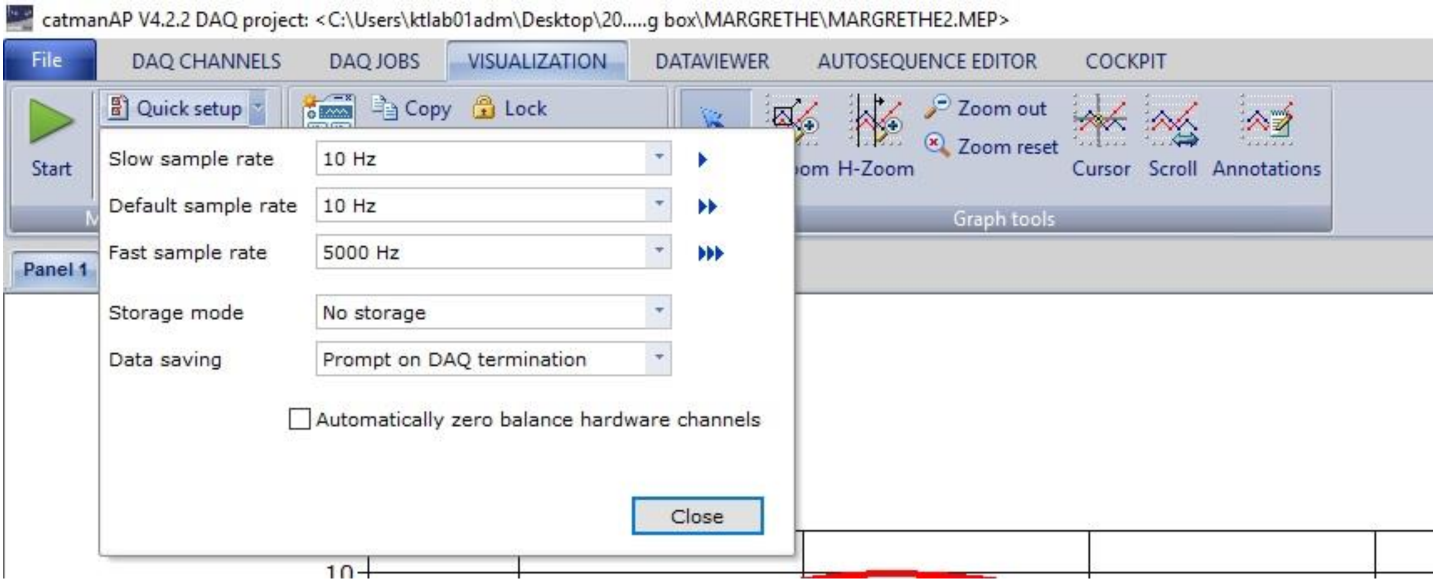
   If you predict the experiment will deflect between ± 0.1 [mm], position the fotonic sensor in the middle of Range 1, where I ≈ 3.750 [V]. (As shown below)

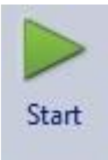
   If you predict the experiment will deflect between ± 1 [mm], position the fotonic sensor in the middle of Range 2, where I ≈ 7.710 [V].

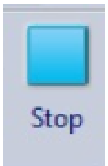


2) If you’ve followed A.3, the specimen’s temperature should be 20[°C]. Make sure catman®Easy has the following setting:

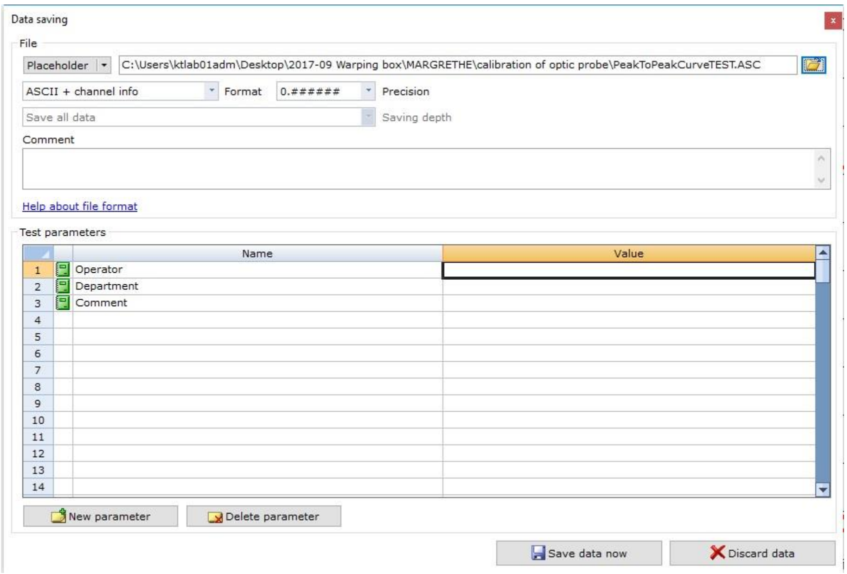
   a. Go to VISUALIZATION. Click on “Quick setup”. Set the Default sample rate to **“0,05 Hz”.** Set the storage mode to **“Keep all data”:**



3) On Julabo, program your temperature cycle. Please refer to A.2.6.
4) Start the temperature cycle on Julabo
5) On catman®Easy, make sure panel 2 is showing on the computer's screen. Then press "Start". 

6) Wait until the temperature cycle is completed.
7) On catman®Easy, press "Stop". 

8) Save the logged data as an "ASC II" file



Appendix B

PHASE 1: WORK LOG

B.1 FINDING THE SETTING FOR THE PELTIERS AND JULABO (PHASE 1)

Phase 1 is divided into 3 parts:

- B.1.1 Reliability Experiment
- B.1.2 Peltier Experiment
- B.1.3 Julabo Experiment

For the Peltier Experiment and Julabo Experiment a series of tests were performed to find the Peltier's $V_{Peltier}$ [V]and Julabo's T_{Julabo}[ºC] settings that are required to make the specimen's temperature equal the specimen's targeted temperature:

$$T_{specimen,above} = T_{specimen,target}[\text{ºC}].$$

This was found through trial-and-error.

For the Reliability Experiment, a series of tests were performed to determine how reliability of the different equipment used with the freeze-warping box.

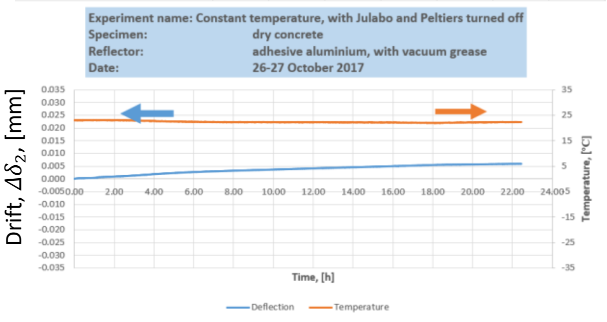
B.1.1 RELIABILITY EXPERIMENT

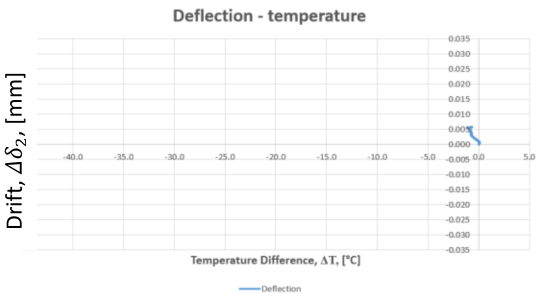
OPTIC PROBE AND FOTONIC SENSOR

Outside disturbances can affect the measurements of a freeze-warping box test, and cause its test results to be scrapped.

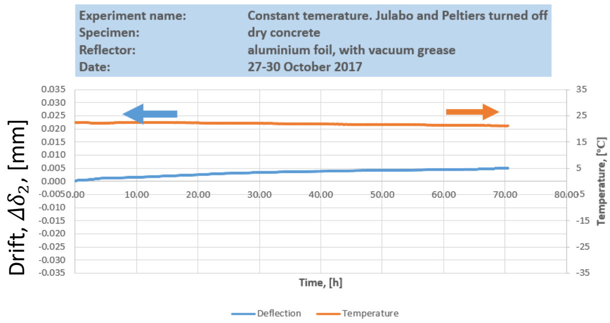
Two tests with both Julabo and Peltiers switched *off* were performed. The goal with these tests was to check if the vibrations form Julabo and the circulating cooling liquid in the tubes may have cause any unwanted drift $\Delta\delta_2$. Both tests showed negligible drift $\Delta\delta_2$.

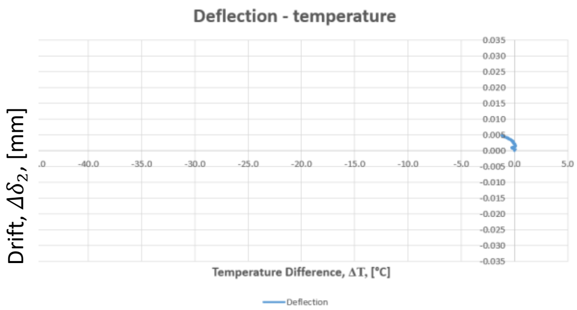
TEST 1 – Dry Concrete 26-27 October 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Dry Concrete, with aluminum foil and vacuum grease	
Time [h]	22
Julabo [°C]	Off
Peltier [V]	Off
Target temperature in freeze-warping box [°C]	Room Temp
REAL temperature, over beam [°C]	-
Drift $\Delta\delta$	5.9 [µm]





TEST 2 – Dry Concrete 27-30 October 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Dry Concrete, with aluminum foil and vacuum grease	
Time [h]	70
Julabo [°C]	Off
Peltier [V]	Off
Target temperature in freeze-warping box [°C]	Room Temp
REAL temperature, over beam [°C]	-
Drift $\Delta\delta$	5.0 [µm]





JULABO

Several freeze-warping box tests were run between September and December. Between November-December, Julabo began to frequently shut down. One of the reasons for this is the rapid evaporation of the cooling liquid ethanol. When ethanol is heated up to $T_{Julabo} = 45.8$[°C] over an extended time period, a large volume of ethanol will rapidly evaporate. When there is not enough cooling liquid in Julabo, it stops working. Several attempted freeze-warping box tests were scrapped due to Julabo's unreliability.

To reduce the amount of evaporated ethanol, butyl tape was added around the rim of Julabo's lid. This has reduced (but not eliminated) the frequency of Julabo's shut downs.

CATMAN®EASY AND QUANTUM X

The program catman®Easy has generally been very reliable. However, it has on rare occasions stopped working midway through a freeze-warping box test. The causes behind this are unknown.

OPTIC PROBE

Two series of calibration tests were performed to check if the measured calibration curves are reliable. Two test series were made; the fotonic sensor/optic probe was calibrated once, then the calibration curve was **run** multiple times at different points in time**.** Their functions for range 1 and range 2 are then compared with one another with the following equations:

Change in the slope for range 1: $\Delta m_1 = \left(\frac{m_{1,run\,i} - m_{1,run\,1}}{m_{1,run\,1}}\right) 100\ [\%]$

Change in the slope for range 2: $\Delta m_2 = \left(\frac{m_{2,run\,i} - m_{2,run\,1}}{m_{2,run\,1}}\right) 100\ [\%]$

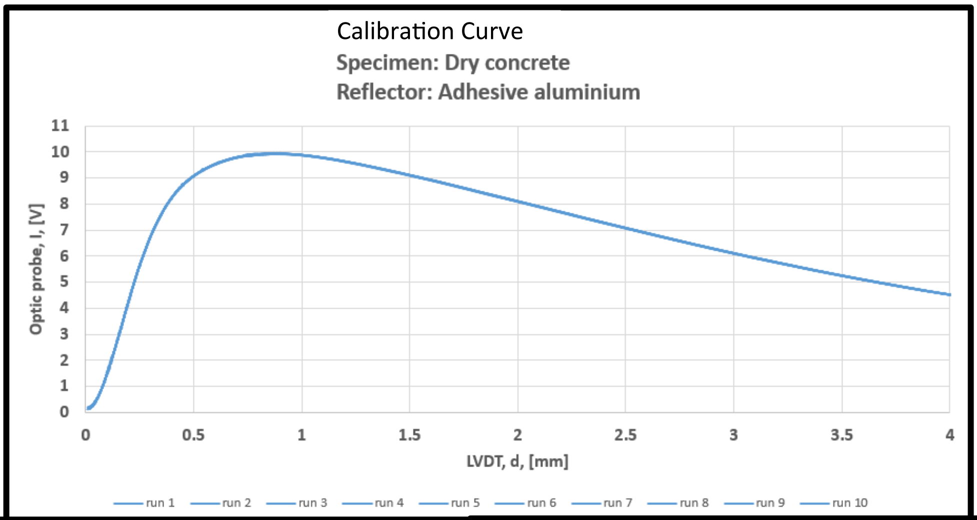
Change in the intercept for range 1: $\Delta b_1 = \left(\frac{b_{1,run\,i} - b_{1,run\,1}}{b_{1,run\,1}}\right) 100\ [\%]$

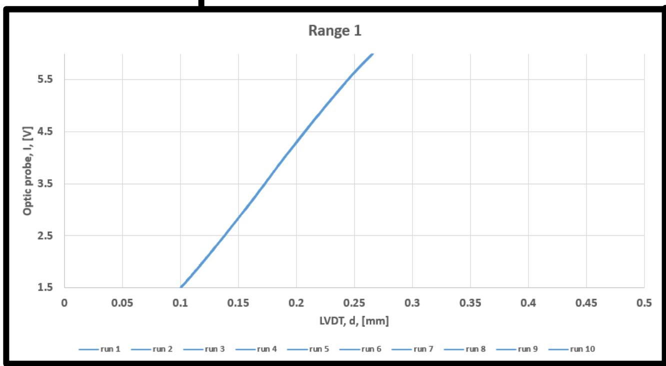
Change in the intercept for range 1: $\Delta b_2 = \left(\frac{b_{2,run\,i} - b_{2,run\,1}}{b_{2,run\,1}}\right) 100\ [\%]$

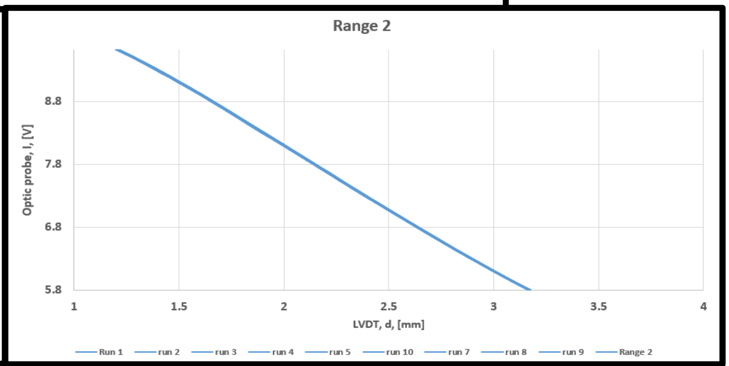
index: i = run number

The results from both tests showed the calibration curves were repeatable. Test 2 showed that the calibration stretches upwards after a day.

TEST 1 **Finding the calibration curve** **Specimen: Dry concrete, with adhesive aluminum and vacuum grease**	
18 September 2017	
15:37	The fotonic sensor/optic probe was calibrated
15:37-16:06	**Run 1-10** were performed. Their calibration curves are shown in blue.







		1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
RANGE 1	m_1	27.90	27.95	27.83	28.11	27.88	28.24	27.86	28.12	27.91	28.05
	b_1	-1.32	-1.33	-1.31	-1.36	-1.33	-1.38	-1.32	-1.36	-1.33	-1.35
	Δm_1	0.00	0.21	-0.25	0.76	-0.05	1.24	-0.13	0.79	0.06	0.55
	Δb_1	0.00	0.56	-1.01	3.07	0.73	4.36	-0.04	2.69	0.55	1.72
RANGE 2	m_2	-1.99	-1.99	-1.99	-1.99	-2.00	-2.00	-2.00	-2.00	-2.00	-2.00
	b_2	12.06	12.08	12.07	12.09	12.09	12.09	12.09	12.10	12.10	12.10
	Δm_2	0.00	0.04	0.06	0.10	0.32	0.17	0.32	0.18	0.50	0.23
	Δb_2	0.00	0.17	0.08	0.20	0.22	0.25	0.23	0.29	0.34	0.31

Average: $\overline{m_1} = \frac{\sum m_1}{10} = 27.98$, Standard deviation: $\overline{STDm_1} = \sqrt{\frac{\sum(m_1 - \overline{m_1})^2}{10-1}} = 0.14$

Average: $\overline{m_2} = \frac{\sum m_2}{10} = -2.00$, Standard deviation: $\overline{STDm_2} = \sqrt{\frac{\sum(m_2 - \overline{m_2})^2}{10-1}} = 0.00$

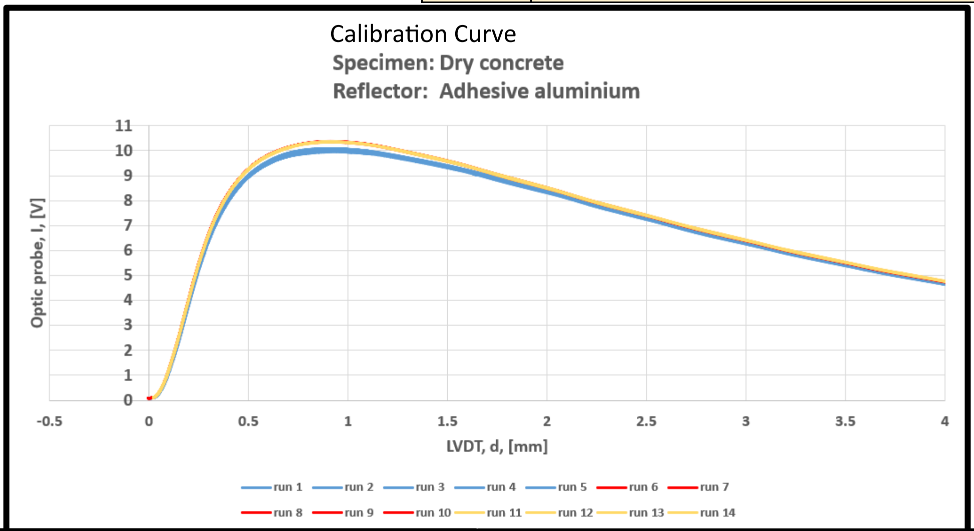
Average: $\overline{b_1} = \frac{\sum b_1}{10} = -1.32$, Standard deviation: $\overline{STDb_1} = \sqrt{\frac{\sum(b_1 - \overline{b_1})^2}{10-1}} = 0.02$

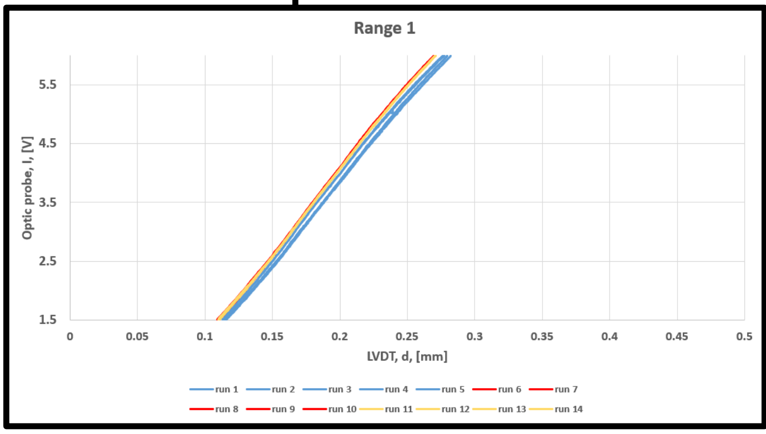
Average: $\overline{b_2} = \frac{\sum b_2}{10} = 12.09$, Standard deviation: $\overline{STDb_2} = \sqrt{\frac{\sum(b_2 - \overline{b_2})^2}{10-1}} = 0.01$

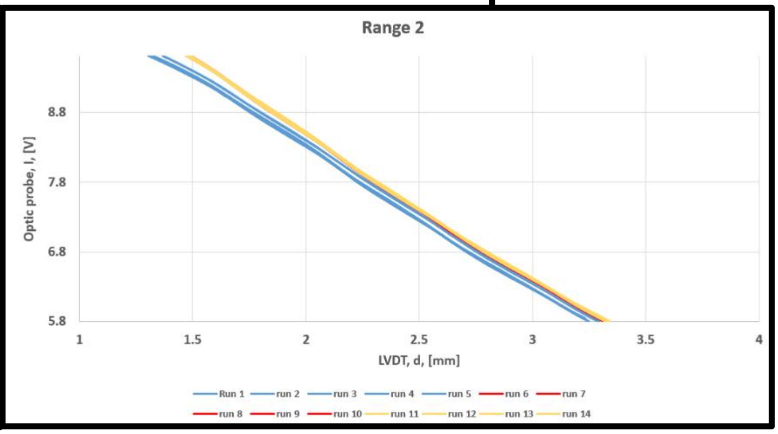
The results from Test 1 shows minimal changes (small standard deviation) to the Calibration Curve when it is re-drawn multiple times. Run 1-10 were all drawn within 30 min. It was speculated that the Calibration Curve may change if it were to be redrawn after a longer time period. Test 2 was therefore performed.

TEST 2
Finding the Calibration Curve
Specimen: Dry concrete, with adhesive aluminum and vacuum grease

20 September 2017		**21 September 2017**	
14:00	The fotonic sensor/optic probe was calibrated	00:00-09:20	The fotonic sensor was left on overnight.
14:00-14:45	**Run 1-5** were performed. Their Calibration Cureves are shown as blue	09:20-09:40	**Runs 5-10** were performed. Their Calibration Curves are shown as red
14.45-23:59	The fotonic sensor was left on overnight.	09:40	The fotonic sensor was switched on and off
		10:25-10:50	**Runs 11-14** were performed. Their Calibration Curves are shown as yellow







		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14
RANGE 1	m_1	28.18	28.20	28.02	27.75	28.03	29.07	28.77	28.95	28.75	28.97	28.67	28.80	28.64	28.83
	b_1	-1.67	-1.69	-1.75	-1.74	-1.75	-1.74	-1.68	-1.73	-1.68	-1.73	-1.68	-1.72	-1.68	-1.72
	Δm_1	0.00	0.04	-0.57	-1.53	-0.56	3.15	2.07	2.71	2.01	2.78	1.72	2.20	1.63	2.28
	Δb_1	0.00	1.41	5.07	4.27	5.00	4.14	0.61	3.47	0.64	3.85	0.82	2.77	0.38	2.71
RANGE 2	m_2	-2.03	-2.05	-2.05	-2.05	-2.05	-2.13	-2.11	-2.11	-2.11	-2.11	-2.10	-2.10	-2.10	-2.10
	b_2	12.35	12.41	12.38	12.47	12.47	12.74	12.69	12.73	12.70	12.73	12.68	12.69	12.69	12.70
	Δm_2	0.00	0.75	0.55	0.60	0.57	4.67	3.66	3.93	3.55	3.70	3.23	3.04	3.26	3.07
	Δb_2	0.00	0.45	0.21	0.99	0.94	3.17	2.76	3.06	2.79	3.05	2.66	2.75	2.71	2.85

Day 1 (run 1-5)

Average: $\overline{m_1} = \frac{\sum m_1}{10} = 28.04$, Standard deviation: $\overline{STDm_1} = \sqrt{\frac{\sum(m_1-\overline{m_1})^2}{10-1}} = 0.18$

Average: $\overline{m_2} = \frac{\sum m_2}{10} = -2.04$, Standard deviation: $\overline{STDm_2} = \sqrt{\frac{\sum(m_2-\overline{m_2})^2}{10-1}} = 0.01$

Average: $\overline{b_1} = \frac{\sum b_1}{10} = -1.72$, Standard deviation: $\overline{STDb_1} = \sqrt{\frac{\sum(b_1-\overline{b_1})^2}{10-1}} = 0.04$

Average: $\overline{b_2} = \frac{\sum b_2}{10} = 12.42$, Standard deviation: $\overline{STDb_2} = \sqrt{\frac{\sum(b_2-\overline{b_2})^2}{10-1}} = 0.05$

Day 2 (run 6-10)

Average: $\overline{m_1} = \frac{\sum m_1}{10} = 28.90$, Standard deviation: $\overline{STDm_1} = \sqrt{\frac{\sum(m_1-\overline{m_1})^2}{10-1}} = 0.14$

Average: $\overline{m_2} = \frac{\sum m_2}{10} = -2.11$, Standard deviation: $\overline{STDm_2} = \sqrt{\frac{\sum(m_2-\overline{m_2})^2}{10-1}} = 0.01$

Average: $\overline{b_1} = \frac{\sum b_1}{10} = -1.72$, Standard deviation: $\overline{STDb_1} = \sqrt{\frac{\sum(b_1-\overline{b_1})^2}{10-1}} = 0.03$

Average: $\overline{b_2} = \frac{\sum b_2}{10} = 12.72$, Standard deviation: $\overline{STDb_2} = \sqrt{\frac{\sum(b_2-\overline{b_2})^2}{10-1}} = 0.02$

Day 2 after the fotonic sensor has been switched off and on (run 11-14)

Average: $\overline{m_1} = \frac{\sum m_1}{10} = 28.74$, Standard deviation: $\overline{STDm_1} = \sqrt{\frac{\sum(m_1-\overline{m_1})^2}{10-1}} = 0.19$

Average: $\overline{m_2} = \frac{\sum m_2}{10} = -2.10$, Standard deviation: $\overline{STDm_2} = \sqrt{\frac{\sum(m_2-\overline{m_2})^2}{10-1}} = 0.00$

Average: $\overline{b_1} = \frac{\sum b_1}{10} = -1.70$, Standard deviation: $\overline{STDb_1} = \sqrt{\frac{\sum(b_1-\overline{b_1})^2}{10-1}} = 0.02$

Average: $\overline{b_2} = \frac{\sum b_2}{10} = 12.69$, Standard deviation: $\overline{STDb_2} = \sqrt{\frac{\sum(b_2-\overline{b_2})^2}{10-1}} = 0.01$

The results show that when the fotonic sensor is left on for about 1 [day], the Calibration Curve stretches up (compare the red lines to the blue lines). This can be seen with the slopes for both Range 1 and Range 2 which have increased from $m_1 = 28.04\ to\ 28.90$ and $m_2 = 2.04\ to\ 2.11$.

When the fotonic sensor is turned off and on, there is negligible changes to the Calibration Curve (compare the red lines to the yellow lines).

B.1.2 PELTIER EXPERIMENTS

A series of freeze-warping box tests called **Julabo Experiment** are performed. The goal of the Peltier Experiment is to find the Peltiers' setting $V_{Peltier}$ that gives the targeted specimen temperature $T_{specimen,target}$. The following series of experiments are color coded:

- The Peltier setting in the green cells shows where $T_{specimen} > T_{specimen,target}$. This can be corrected by increasing $V_{Peltier}$.
- The Peltier setting in the red cells shows where $T_{specimen} < T_{specimen,target}$. This can be corrected by decreasing $V_{Peltier}$.
- The Peltier setting in the blue cells shows where $T_{specimen} = T_{specimen,target} \mp 1[°C]$. In these cells, there is no need to correct the setting of the Peltiers $V_{Peltier}$.

The Peltiers' settings are kept constant $V_{Peltier} = constant$.

Two types of specimens were used; dry concrete specimen and invar specimen.

DRY CONCRETE SPECIMEN

TEST 1 – Dry Concrete Specimen 16 October 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Dry concrete, with adhesive aluminum and vacuum grease				
Time, t [h]	0.1	0.7	1.3	1
Julabo, T_{Julabo} [°C]	20	20	20	20
Peltier, $V_{Peltier}$ [V]	0.25	1.45	2.85	0.25
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	15	10	20
REAL temperature, over beam, $T_{specimen,above}$ [°C]	20.33456	16.48934	10.57052	20.94643413

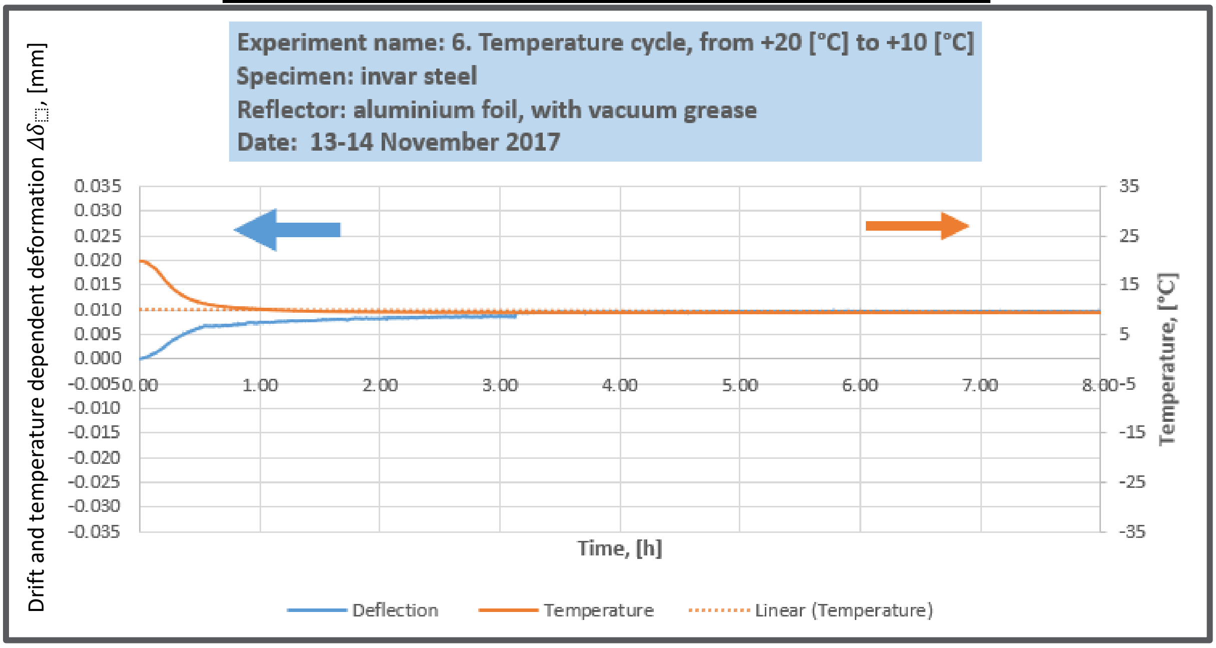
TEST 2 – Dry Concrete Specimen 3 November 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Dry concrete, with aluminum foil and vacuum grease										
Time, t [h]	0	1	1	1	1	1	1	1	1	11
Julabo, T_{Julabo} [°C]	20	20	20	20	20	-12.5	-12.5	-12.5	-12.5	20
Peltier, $V_{Peltier}$ [V]	0.35	1.45	2.9	4.5	6.5	0.6	1.75	3.5	5.45	0.35
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	15	10	5	0	-5	-10	-15	-20	20
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.7	15.6	10.3	5.3	0.4	-4.4	-9.1	-13.3	-18.7	20.9

INVAR SPECIMEN

The dry concrete specimen used in the tests above is made up of cement and aggregate, making it in-homogenous. This may cause some bending during a freeze-thaw cycle. To avoid any specimen deflection, the specimen was then exchanged with a homogenous invar steel specimen.

The *Peltier's setting* $V_{Peltier}$ *required to meet the specimen's targeted temperature* $T_{specimen,target}$ *depends on the specimen's material and size*. The Peltier setting used for the dry concrete specimen are therefore adjusted accordingly for the invar steel specimen.

TEST 1 – Invar Specimen 3 November 2017 – Temperature cycle from +20 [°C] to +10 [°C] Specimen: Invar steel, with aluminum foil and vacuum grease		
Time, t [h]	0	19.5
Julabo, T_{Julabo} [°C]	20	20
Peltier, $V_{Peltier}$ [V]	0.35	2.9
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	10
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.8	9.4



The goal of *TEST 1 – Invar Specimen* was to measure the time $\boldsymbol{t[h]}$ required for the **specimen's temperature** $\boldsymbol{T_{specimen,above}}$ and the freeze-warping box's **temperature dependent deflection and drift** $\boldsymbol{\Delta\delta}$**[mm]** to reach equilibrium.

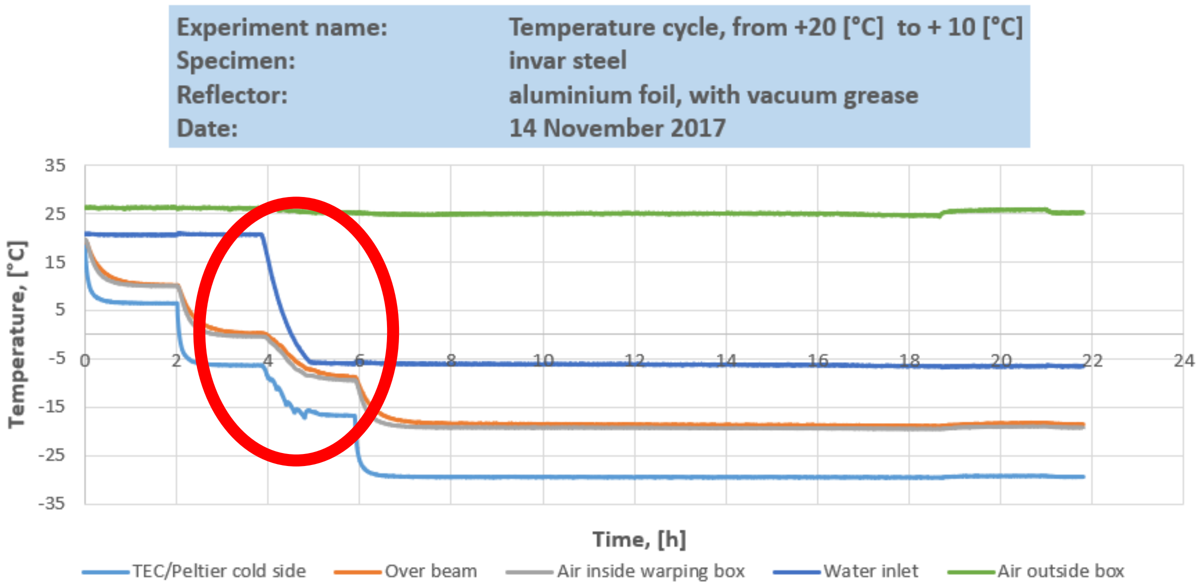
- From the Deflection-Time diagram, it takes roughly $t = 3\ [h]$ for $\Delta\delta$[mm] to reach equilibrium.
- From the Temperature-Time diagram, it takes roughly 1 [h] for the specimen's temperature $T_{specimee}$ to reach equilibrium.

TEST 2 – Invar Steel 3 November 2017 – Temperature cycle from +20 [°C] to +10 [°C] Specimen: Invar steel, with aluminum foil and vacuum grease				
Time, t [h]	0	1	1	2
Julabo, T_{Julabo} [°C]	20	20	20	20
Peltier, $V_{Peltier}$ [V]	0.35	1.45	2.9	0.35
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	15	10	20
REAL temperature, over beam, $T_{specimen,above}$ [°C]	20.0	15.8	10.5	19.4

TEST 3 – Invar Steel 14 November 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aludinum foil and vacuum grease					
Time, t [h]	0	2	2	2	16
Julabo, T_{Julabo} [°C]	20	20	20	-12.5	-12.5
Peltier, $V_{Peltier}$ [V]	0.35	2.9	6.5	1.75	5.45
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	10	0	-10	-20
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.4	10.2	0.3	-8.7	-17.8516

IMPRACTICALITY ISSUES

When a freeze-warping box experiment is being performed, and the specimen's temperature is controlled by the Peltier's setting $V_{Peltier}$, currently the only way to adjust $V_{Peltier}$ is by adjusting the Peltiers manually. This means the person using the freeze-warping box must stay within proximity of the freeze-warping box throughout the entire experiment. This is inconvenient for the person using the freeze-warping box, especially if the freeze-warping box test is being run for several hours.



$T_{specimen,above}$[°C] $T_{air,inside}$[°C] $T_{air,outside}$[°C] $T_{peltier,cold}$[°C] T_{inlet}[°C]

When the specimen's temperature $T_{specimen}$ decreases from 0[°C] to -10 [°C], Julabo's temperature setting must decrease from $T_{Julabo} = 20$[°C] to -12.5[°C]. (See red ring in the figure above). Whiles Julabo's temperature decreases, the Peltiers need to be gradually adjusted. Adjustments are done manually. The person running the freeze-warping box is required to stay close to the freeze-warping box and pay full attention to Julabo's temperature T_{Julabo} and the Peltiers' settings $V_{Peltier}$ for the next 1.5[h]. This is tedious. Julabo gives of a strong smell of ethanol, which makes it uncomfortable for the person to sit in front of the freeze-warping box for an extended period of time.

It is more practical to run the freeze-warping box test with Julabo's temperature setting T_{Julabo}. Julabo's temperature setting can be programmed to run within a time specified cycle. This means the person running the freeze-warping box test only needs to visit the freeze-warping box twice:

- before the freeze-warping box test, to set up the equipment, and program Julabo's temperature cycle.
- after the freeze- warping box test.

Further tests for the **Peltier Experiment** was therefore dropped in favor of the **Julabo Experiment.**

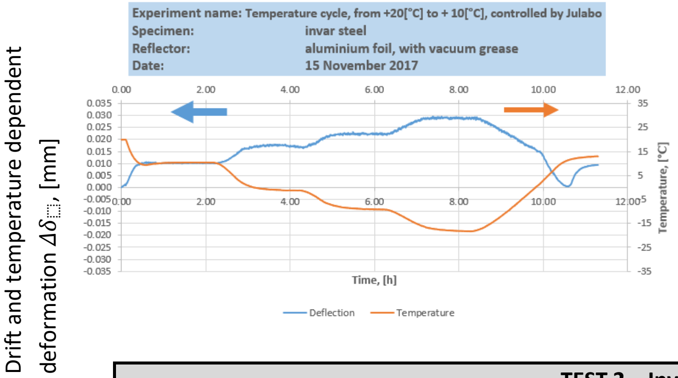
B.1.3 JULABO EXPERIMENTS

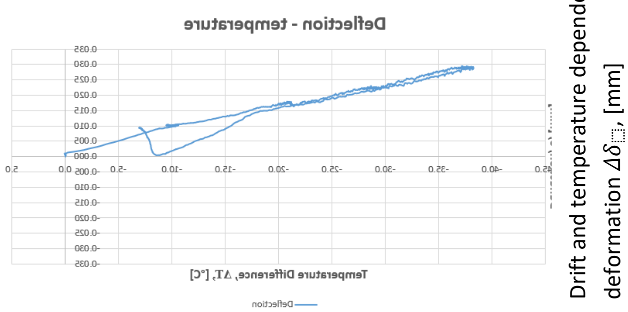
A series of freeze-warping box tests called **Julabo Experiment** are performed. The goal is to find the necessary settings for Julabo's temperature T_{Julabo} to reach a specimen's targeted temperature $T_{specimen,target}$. The following series of experiments are color coded:

- The green cells show where $T_{specimen,above} > T_{specimen,target}$. This can be corrected by decreasing T_{Julabo} .
- The red cells show where $T_{specimen,above} < T_{specimen,target}$. This can be corrected by increasing T_{Julabo} .
- The blue cells show where $T_{specimen,above} = T_{specimen,target} \mp 1[°C]$. In these cells, there is no need to correct the setting of T_{Julabo}

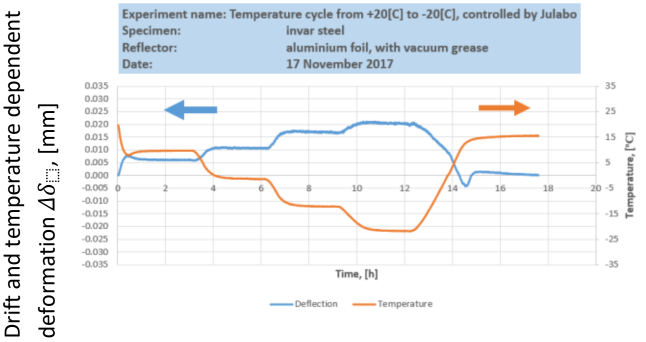
The Peltiers' settings are kept constant $V_{Peltier} = constant$.

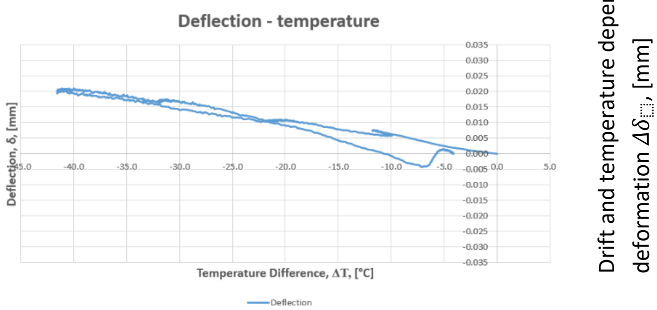
TEST 1 – Invar Steel 15 November 2017 – Temperature cycle from +20 [ºC] to -20 [ºC] Specimen: Invar steel, with aluminum foil and vacuum grease						
Time, t [h]	2	2	2	2	2	3
Julabo, T_{Julabo} [°C]	32.5	32.5	15	2.5	-12.5	37.5
Peltier, $V_{Peltier}$ [V]	0.30	5.60	5.60	5.60	5.60	5.60
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	10	0	-10	-10	20
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.9	10.4	-1.2	-9.2	-18.2	13.0





TEST 2 – Invar Steel 17 November 2017 – Temperature cycle from +20 [ºC] to -20 [ºC] Specimen: Invar steel, with aluminum foil and vacuum grease						
Time, t [h]	0	3	3	3	3	5
Julabo, T_{Julabo} [°C]	20	32.5	17	1	-14	40
Peltier, $V_{Peltier}$ [V]	0.30	5.60	5.60	5.60	5.60	5.60
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	10	0	-10	-20	20
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.7	9.7	-1.5	-12.2	-21.8	15.5



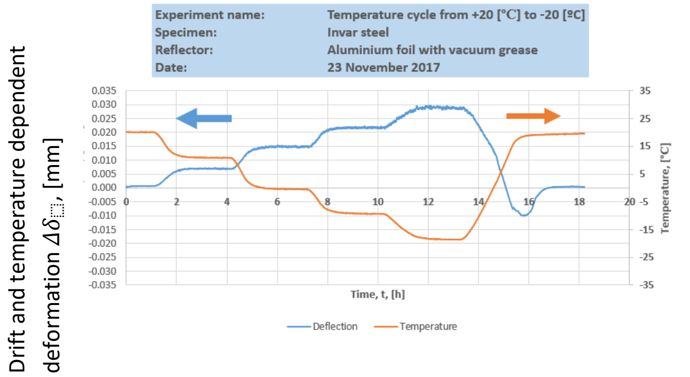


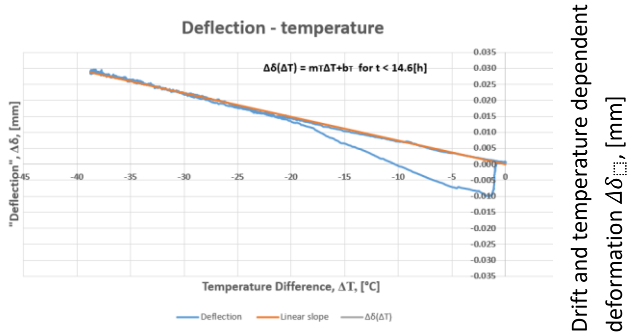
For tests 1 and 2, a temperature cycle from +20[ºC] to -20[ºC] was attempted. At the beginning of a temperature cycle, the Peltiers' settings were set at 0.30 [V] and Julabo was set at 32.5[ºC]. The purpose of the lower Peltier setting at the beginning was to check if it is possible achieve $T_{specimen,above} = 20$ [ºC] with a low T_{Julabo}, and minimize the volume of ethanol evaporating from Julabo.

Between 0 [h] – 1 [h], $T_{specimen,above}$ reduces from 20 [C] to 10[C]. During this hour, the Peltiers' setting was gradually increased from 0.3 [V] to 5.60 [h]. This requires a person to sit in front of the freeze-warping box for an hour to manually adjust the Peltiers for 1[h]. This is very impractical.

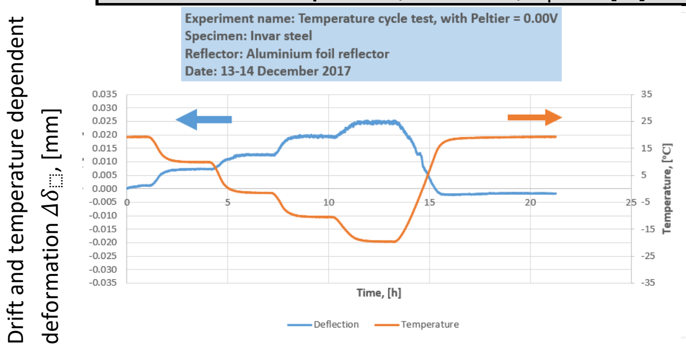
For the next tests (3, 4, and 5) it was decided to make the Peltiers' setting constant through the entire duration of temperature cycle tests.

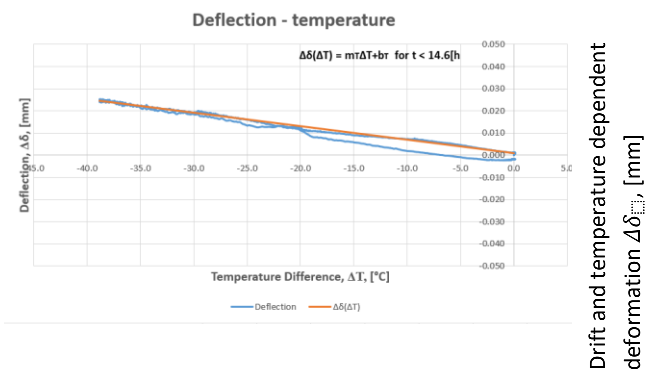
TEST 3 – Invar Steel 23 November 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil and vacuum grease						
Time, t [h]	1	3	3	3	3	3+
Julabo, T_{Julabo} [°C]	45.8	32.5	15.7	2	-13	45.8
Peltier, $V_{Peltier}$ [V]	5.70	5.70	5.70	5.70	5.70	5.70
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	10	0	-10	-20	20
REAL temperature, over beam, $T_{specimen}$ [°C]	20.1	10.9	-0.4	-9.3	-18.5	19.6



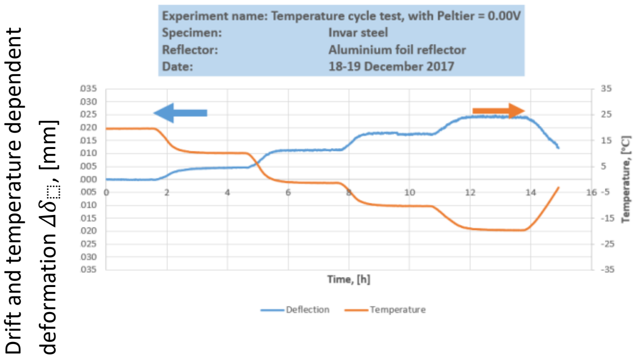


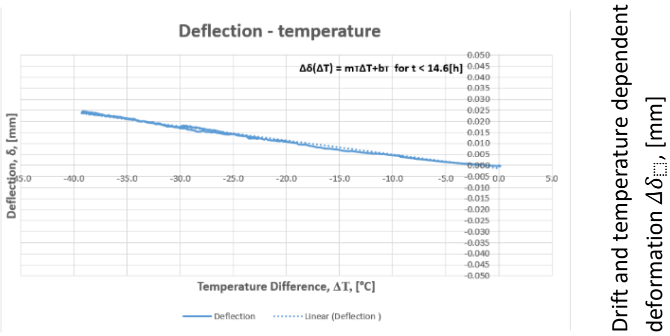
TEST 4 13 December 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil and vacuum grease						
Time, t [h]	1	3	3	3	3	3+
Julabo, T_{Julabo} [°C]	48.5	32.5	15.7	2	-13	45.8
Peltier, $V_{Peltier}$ [V]	5.70	5.70	5.70	5.70	5.70	5.70
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	10	0	-10	-20	20
REAL temperature, over beam, $T_{specimen}$ [°C]	19.2	9.9	-1.5	-10.5	-19.6	19.2





TEST 5 18 December 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil and vacuum grease						
Time, t [h]	1	3	3	3	3	3+
Julabo, T_{Julabo} [°C]	48.5	32.5	15.7	2	-13	45.8
Peltier, $V_{Peltier}$ [V]	5.70	5.70	5.70	5.70	5.70	5.70
Target temperature in freeze-warping box, $T_{specimen,target}$ [°C]	20	10	0	-10	-20	20
REAL temperature, over beam, $T_{specimen}$ [°C]	19.6	10.1	-1.4	-10.3	-19.1	N/A





Tests 3-5 have the same temperature-cycle. This temperature-cycle was run three times to show that the measured **drift and temperature dependent deformation Δδ**, and **specimen's temperature $\boldsymbol{T_{specimen}}$** stays consistent for each test.

For tests 1-5, between the time the temperature $T < 0$[°C], ice collects inside the freeze-warping box. During the time the temperature increases from T=-20[°C] to T=20[°C], the ice begins to melt. Condensation begins to collect on the reflector tab, causing a dip in the deflection-time curve.

This dip is less noticeable in test 4. It is assumed it is caused by an increased amount of vacuum grease on the reflector tab.

NOTE!

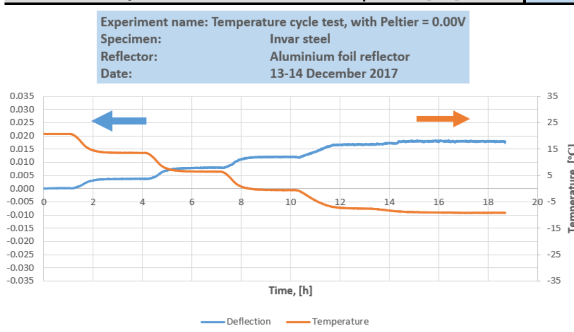
The results from tests 3, 4, and 5 are used in Chapter 3.2.1

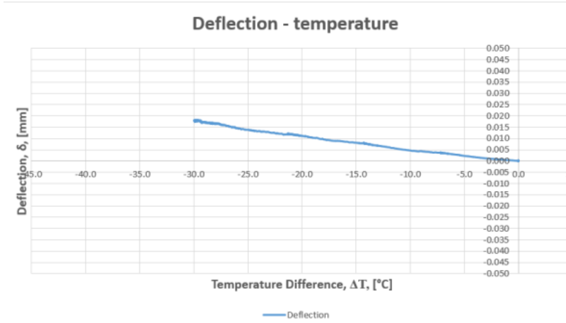
RAPID EVAPORATION OF THE COOLING LIQUID (ETHANOL)

For tests 1, 2, 3, 4, and 5, a large volume of cooling liquid (ethanol) evaporates out of Julabo. (Nearly 1 [L] per day!). Several other tests were attempted with the same temperature cycle as tests 3-5, in which Julabo shut down frequently. One of the reasons for Julabo's frequent shut downs is the decreasing volume of ethanol. When Julabo shuts down, the Peltiers are still running, and the temperature inside the freeze-warping box increases making the specimen's temperature nearly $T_{specimen} = 60$ [°C]. If the freeze-warping box is left unattended with only the Peltiers on at 5.70[V], we run the risk of damaging the Peltiers and the specimen. Test 6 was therefore performed to reduce the evaporation rate of ethanol, and to prevent the specimen and Peltiers from getting damaged.

TEST 6 13 December 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil and vacuum grease						
Time, t [h]	1	3	3	3	3	3+
Julabo, T_{Julabo} [°C]	20	10	0	-10	-20	-22 (the targeted Julabo temperature setting was -30)
Peltier, $V_{Peltier}$ [V]	0	0	0	0	0	0
Target temperature in warping box, $T_{specimen,target}$ [°C]	-	-	-	-	-	-
REAL temperature, over beam, $T_{specimen}$ [°C]	20.7	13.5	6.4	-0.6	-7.6	-9.2

Drift and temperature dependent deformation $\Delta\delta_{\square}$, [mm]





Drift and temperature dependent deformation $\Delta\delta_{\square}$, [mm]

For Test 6, the Peltiers were set to 0 [V], to check if it was possible to achieve a freeze-thaw cycle with *a lower temperature setting for Julabo* T_{Julabo}. After t = 10[h], Julabo's temperature setting was supposed to reach $T_{Julabo} = 30$[°C]. It was instead revealed that Julabo has a lower temperature limit of $T_{Julabo} = -22$ [°C]. The temperature cycle in test 3-5 is therefor used for phase 2 and phase 3.

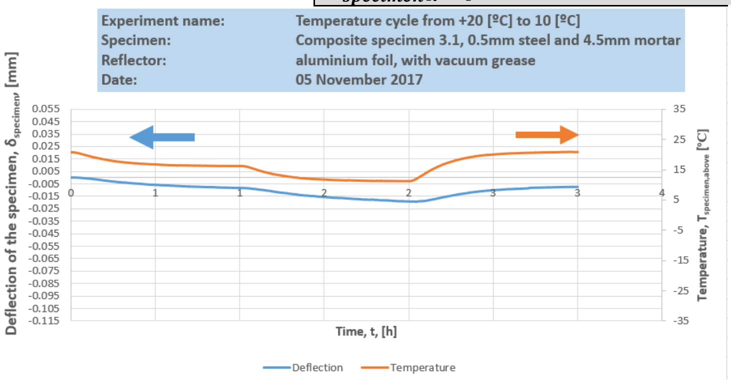
Appendix C

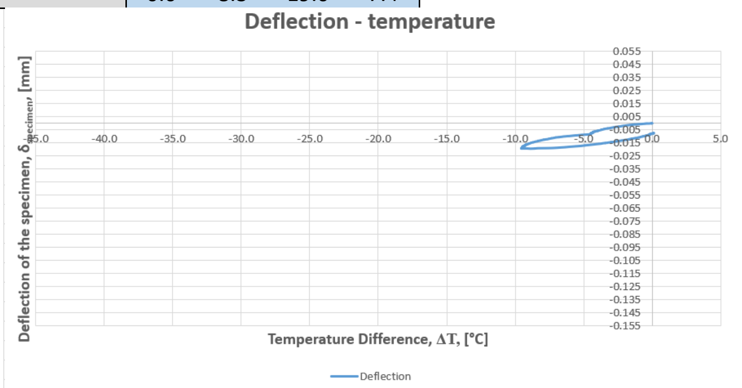
SPECIMEN 3.1

Composite specimen 3.1 went through 2 temperature cycles from +20[°C] to +10[°C].
Due to lack of practice running a temperature cycle in the freeze-warping box, the results for specimen 3.1 were not included in Chapter 3. Additionally, both temperature cycles seem to show a permanent deformation after the cycle is complete. This could mean that composite 3.1 either had or gained damage.
The temperature cycles below were controlled with the Peltiers, unlike the composite 2.1 (chapter 3) which were controlled with Julabo.

TEMPERATURE CYCLE WITH COMPOSITE 3.1-TEST 1

TEMPERATURE CYCLE 1-TEST 1 5 November 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil reflector and vacuum grease				
Time, t [h]	0	1	1	1
REAL temperature, over beam, $T_{specimen,above}$ [°C]	20.7	15.9	-10.3	20.8
$\delta_{specimen}$[μm]	0.0	8.3	19.0	7.4

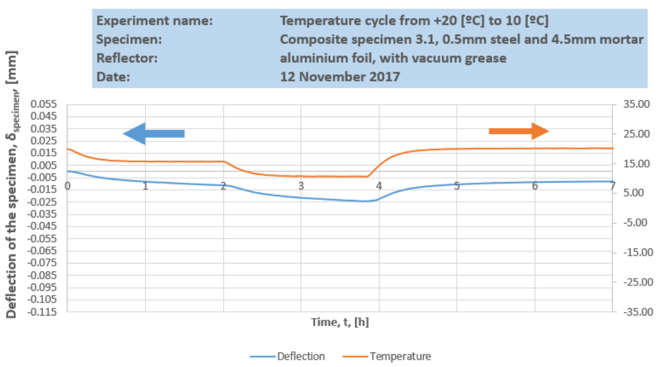


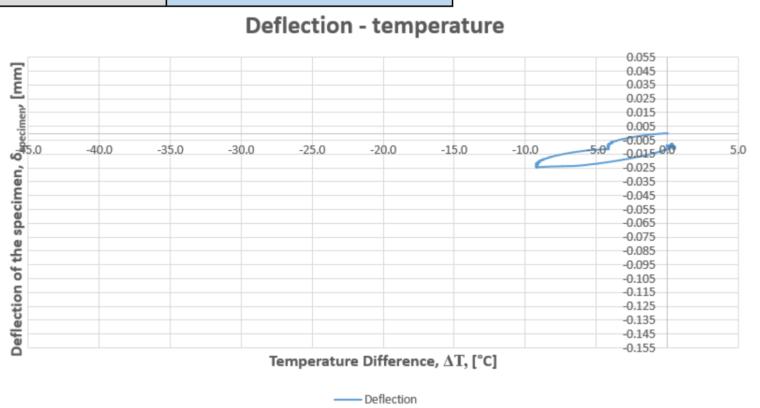


After 1 hour temperature steps, the graphs above show that the specimen's deflection has not been given enough time to reach equilibrium.

TEMPERATURE CYCLE WITH COMPOSITE 3.1-TEST 1

TEMPERATURE CYCLE 1-TEST 1 23 November 2017 – Temperature cycle from +20 [°C] to -20 [°C] Specimen: Invar steel, with aluminum foil reflector and vacuum grease				
Time, t [h]	0	2	2	3
REAL temperature, over beam, $T_{specimen,above}$ [°C]	19.9	15.7	11.3	20.1
$\delta_{specimen}$[μm]	0.0	11.3	24.1	8.2





After 2 hour temperature steps, the graphs above show that the specimen's deflection has not been given enough time to reach equilibrium.