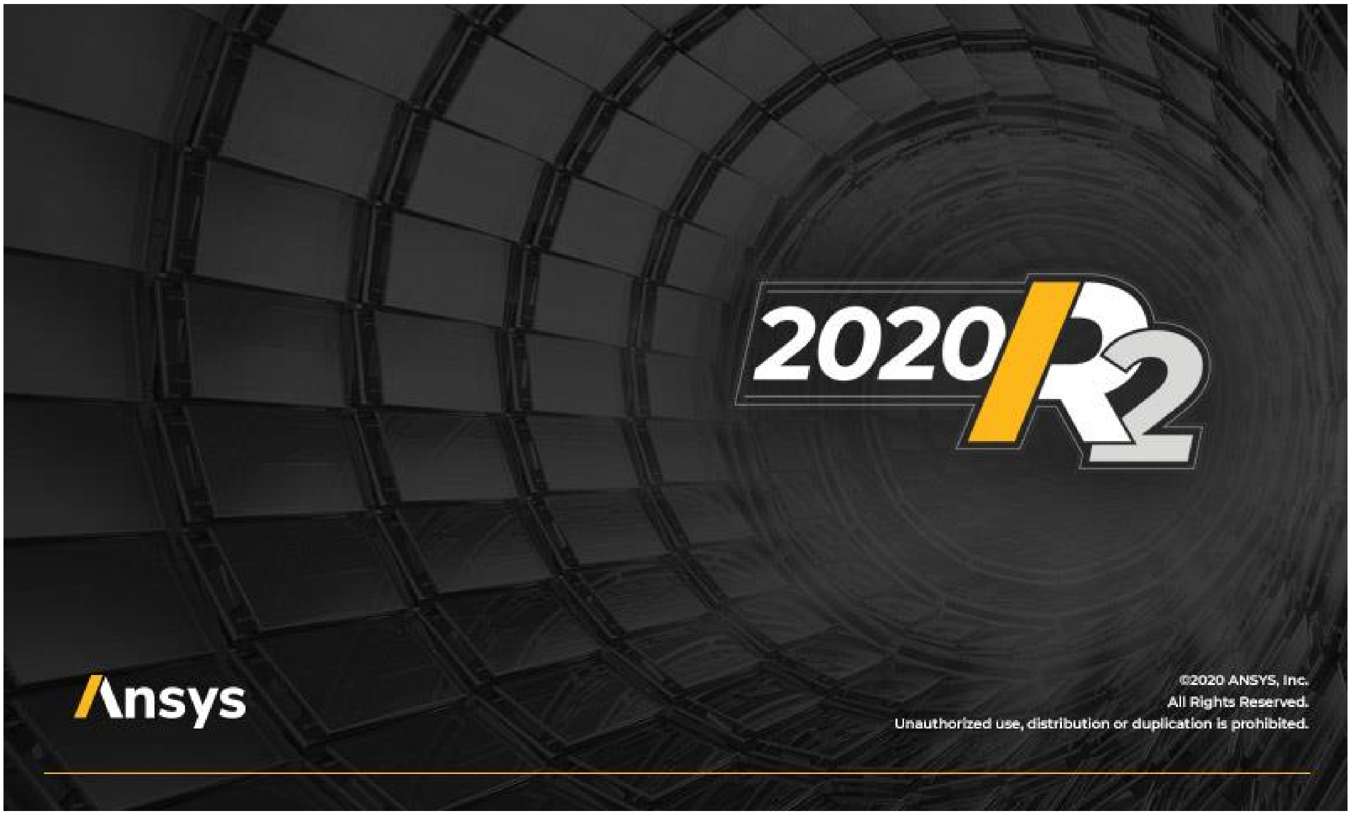

Additive Calibration Guide

ANSYS, Inc.
Southpointe
2600 ANSYS Drive
Canonsburg, PA 15317
ansysinfo@ansys.com
http://www.ansys.com
(T) 724-746-3304
(F) 724-514-9494

Release 2020 R2
July 2020

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Published in the U.S.A.

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Additive Calibration - Quick Start

In order to achieve the best performance of ANSYS Additive software, we highly recommend that you run a distortion calibration process to best fit your simulation to your specific physical manufacturing scenario. This is because actual distortion values from as-built parts vary across different machine and material combinations, especially considering the differences among various laser powder bed fusion (L-PBF) machine manufacturers and powder material suppliers in the market.

A Quick Start Guide (shown below and also available for download as a PDF) summarizes the process for performing an Assumed Strain simulation type using either Linear Elastic or J2 Plasticity stress mode. Refer to the remainder of this Additive Calibration Guide for further details and for information on calibrations with advanced simulation types.

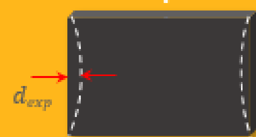
Ansys Additive Distortion Calibration Quick Start Guide

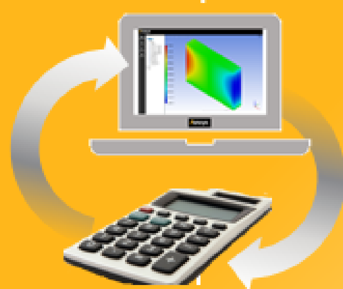
Use this Quick Start Guide to calibrate Ansys Additive software to match your machine/material scenario. The goal is to determine a calibration factor, called a Strain Scaling Factor (SSF), that compensates for the difference between a measured distortion and a simulated distortion. This guide describes the process for performing an Assumed Strain simulation type using either Linear Elastic or J2 Plasticity stress mode.

Step 1

Build & Measure

- Choose a calibration part that is easy to build and yields high distortion
- Build the calibration part with the same process parameters you plan to use for your part
- If possible, build the part directly on the baseplate to minimize support structures
- Allow enough room to make measurements while the part is still attached to the baseplate
- After fabrication, measure displacement (d_{exp}) at location of interest





Step 2

Simulate

- Run Assumed Strain simulation type with the same geometry and material
  - Import your calibration geometry
  - Choose your material
  - Set stress mode = Linear Elastic or J2 Plasticity
  - Set Strain Scaling Factor (SSF) = 1 (default)
  - Use default output options
  - Start the simulation
  - Export On plate stress/displacement
  - Obtain displacement (d_{sim}) at same points and same directional component (X or Y) as measured
- Run new simulation as above but with SSF_{new} calculated in Step 3

Step 3

Calculate & Compare

- Calculate new SSF:

$$SSF_{new} = \frac{d_{exp}}{d_{sim}} SSF_o$$

  where SSF_o is previous SSF
- Compare difference between d_{sim} and d_{exp} until it converges toward zero or an acceptable level
- Record the final SSF_{new} value as $SSF_{cal\ LE}$ or $SSF_{cal\ J2}$
- Create custom materials with SSF_{cal} values in Additive Print

Learn more about Ansys Additive calibration at:
http://storage.ansys.com/doclinks/ansys.html?code=AddCalibration-ALU-M2a

Ansys

Additive Calibration - Full Procedure

Important:

For the most up-to-date calibration procedures and parts, including the Calibration Quick Start Guide as a PDF file, be sure to look at our ANSYS Additive Calibration Files page on the internet.

Objective

The objective of the calibration procedure is to determine the Strain Scaling Factor (SSF) and Anisotropic Strain Coefficients (ASCs) for use in the ANSYS Additive Print software. The calibrated SSFs and ASCs will significantly improve the prediction accuracy of the simulation software, therefore improving the chance of successful builds as well as reducing the cost of trial and error experiments.

Figure 1: SSF required for Assumed Strain simulations in Additive Print

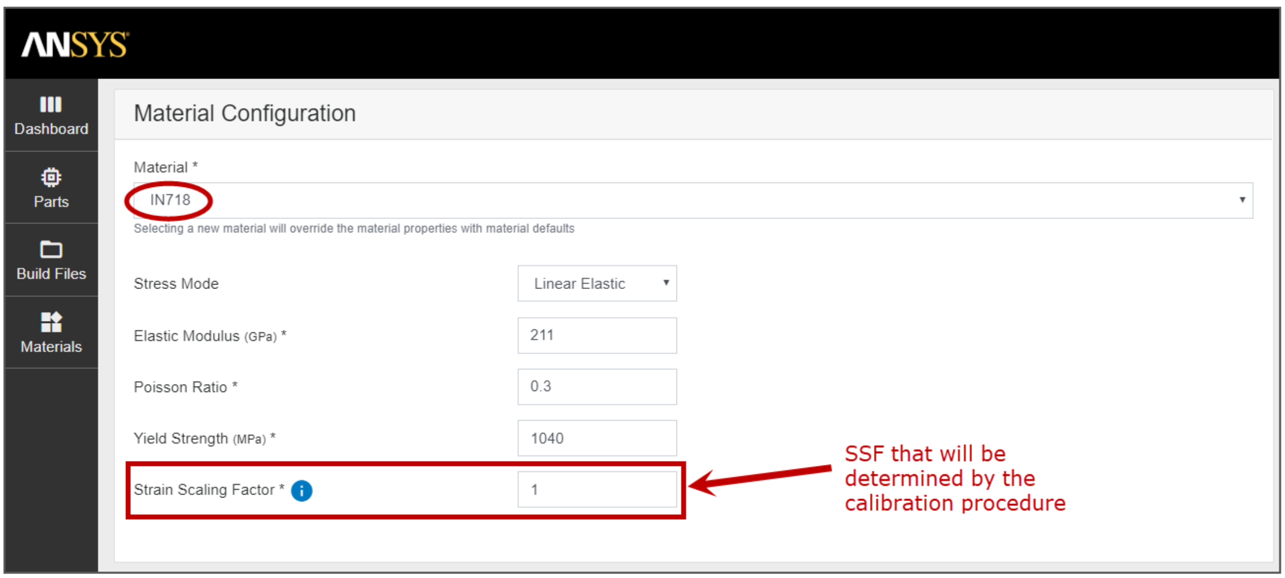
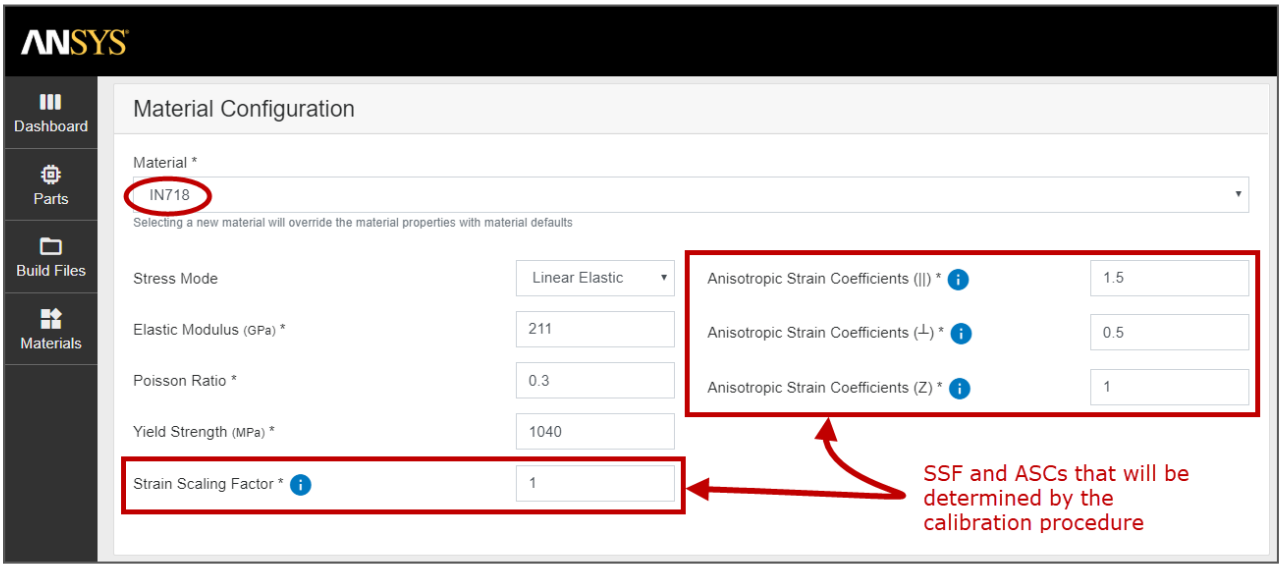


Figure 2: SSF and ASCs required for Scan Pattern and/or Thermal Strain simulations in Additive Print



Procedure

The calibration procedure consists of building parts, taking measurements, running simulations, and calculating factors using a spreadsheet. You will start by building three identical parts using a different scan pattern for each. You'll determine an initial set of SSF and ASC values using the first two scan patterns, and then fine-tune the values with the third scan pattern. Our experience shows that the third scan pattern calibration step increases the accuracy of simulations for user-preferred scan patterns. We *strongly* recommend the fine-tuning step that uses the third scan pattern.

Here is the overall procedure:

1. **Build all calibration parts on the same build plate**

   For convenience, we recommend building all the parts on the same build plate. Use the same part for all calibration steps but use a different scan pattern for each. The dimensions of the part may be adjusted depending on the material, machine, and process parameters to achieve a successful build. The procedure remains the same regardless of part dimensions. More details are available in Building the Parts (p. 9).

2. **Measure the dimensions of the built parts to determine distortion**

   Using the best measurement method available, measure the dimensions of the parts at the recommended locations of interest. Record the dimension measurements in the ANSYS-provided spreadsheet and distortions at those locations will automatically be calculated. More details are available in Taking Distortion Measurements (p. 13).

3. **Run calibration to determine an initial set of factors (for each simulation type and stress mode combination)**

   For a chosen combination of simulation type and stress mode, run simulations of the calibration part in Additive Print. Use the spreadsheet provided to calculate factors based on a distortion average from the first two scan patterns. More details are available in Running the Simulations (p. 17) and Using the Spreadsheet to Calculate SSF and ASCs (p. 21).

4. **Run fine-tuning calibration step with a different scan pattern**

   For the same combination of simulation type and stress mode, run simulations with the newly calibrated factors and use the spreadsheet to fine-tune the factors based on distortion from the third scan pattern.

When to Calibrate

The values for SSF and ASCs depend upon the following:

- Material
- Machine
- Machine parameters (laser power, scan speed, layer thickness, baseplate temperature, hatch spacing, slicing stripe width, scan pattern, etc.)
- Simulation type performed (Assumed Strain, Scan Pattern, or Thermal Strain)
- Stress mode selected (linear elastic or J2 plasticity)

Assuming you perform the full procedure, for each calibration you will have a complete set of values to be used for any simulation type/stress mode *for a given material and machine*. When a different material or machine is chosen, the ASC and SSF values will need to be recalibrated, regardless of the simulation type or stress mode. Even changing the material *supplier* for a material you have already calibrated for may require a new calibration. If the process parameters are altered, Assumed Strain and Scan Pattern-based simulations will need to be recalibrated.

Important:

You need to calibrate only for the type of simulation you will be performing. For example, if you know you will be performing Assumed Strain simulations only, you don't need to build multiple calibration parts because scan pattern doesn't matter and you don't need to complete the calculations for ASCs, as those factors are required only for Scan Pattern and Thermal Strain simulation types. Within your Assumed Strain simulations, if you know you will be using linear elastic stress mode only, there is no need to calibrate for J2 plasticity. See the ANSYS Additive User's Guide for further information about simulation types and stress modes.

Matrix of SSF and ASCs

Table 1 shows a complete matrix across different simulation types and stress modes for a certain material, A. After the full calibration process, you will record final values in the color-filled fields that are unique to that material and machine.

Table 1: Complete matrix of SSF and ASCs

Material	Stress Mode	Assumed Strain		Scan Pattern		Thermal Strain	
A	Linear Elastic	SSF		SSF		SSF	
				ASC		ASC	
				ASC ⊥		ASC ⊥	
				ASC_z	1	ASC_z	1
	J2 Plasticity	SSF		SSF		SSF	
				ASC		ASC	
				ASC ⊥		ASC ⊥	
				ASC_z	1	ASC_z	1

Cantilever Beam Geometry

Geometry files of a **cantilever beam** part and its support, in .stl format, are available for download.

The part dimensions (50 x 10 x 12.5 mm) are shown in Figure 3 (p. 7). The part and its support are shown together in Figure 4 (p. 7). The red dashed line represents the support cutoff location.

Figure 3: Cantilever beam dimensions

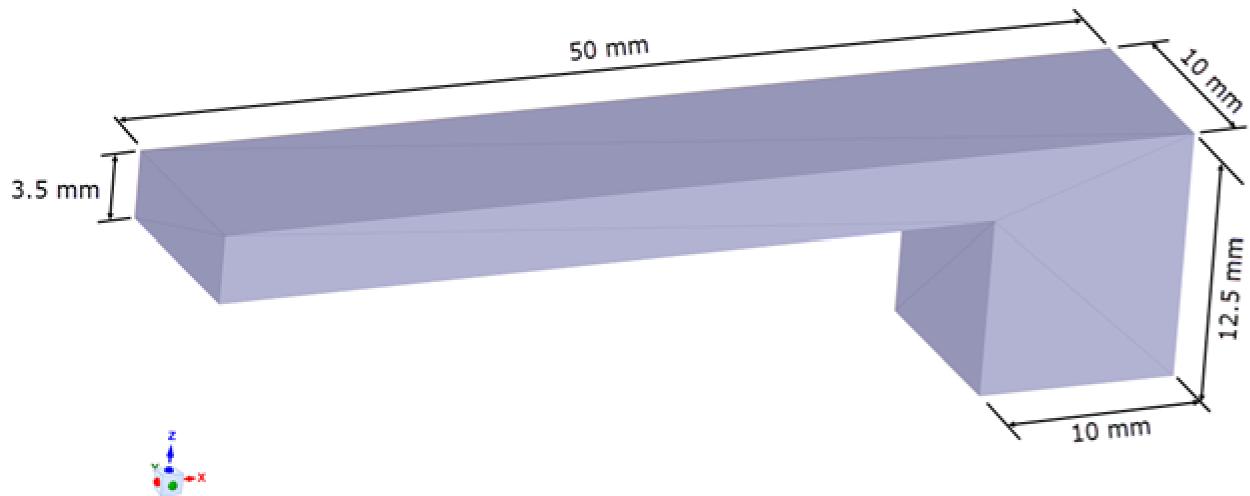
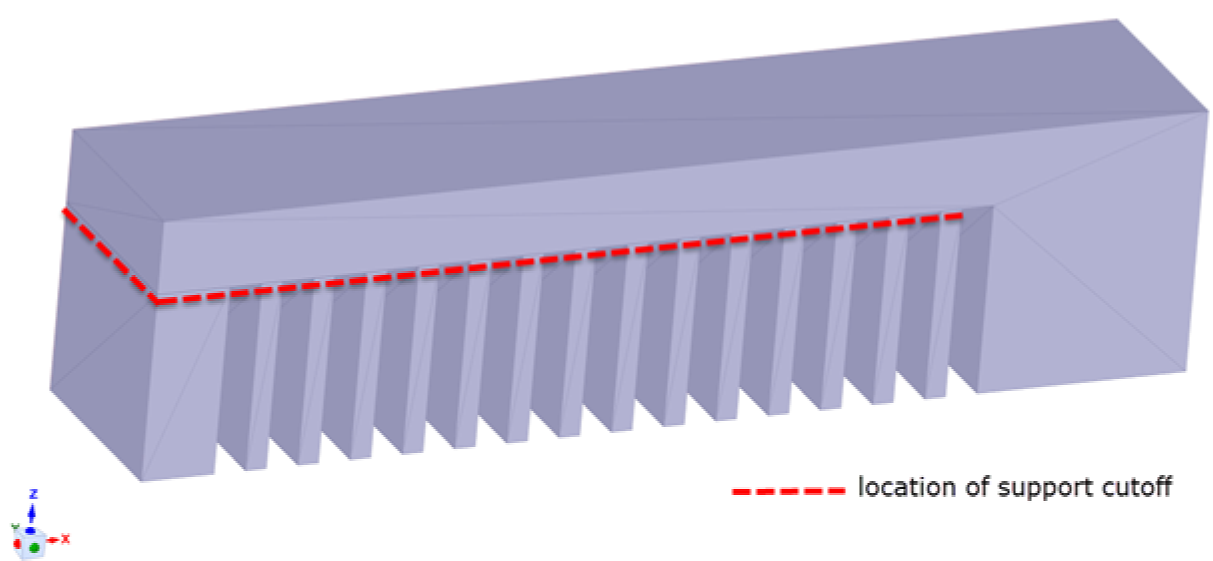


Figure 4: Cantilever beam with support



Building the Parts

Part Layout

We recommend you *build the calibration parts on the same build*. There will be three cantilever beam parts, each with a different scan pattern. The three calibration parts differ only in scan pattern. (If you will be doing Assumed Strain simulations only, then only one part is needed and use the rotating stripe scan pattern.)

Implement an appropriate layout consistent with the best practice for taking gas flow direction into account. Ensure there is enough space between the parts to take measurements *before the parts are cut from the baseplate*. The parts need to be measured while they are fixed to the plate, therefore it is important to keep enough space between neighboring parts.

Support Structure

The support structure of the cantilever beam is provided. The parts should be built on the baseplate directly.

Process Parameters

With the exception of the scan patterns that are described below, the parts should be built with the process parameters (laser power, scan speed, etc.) that you are intending to use for building your real components. Make sure to use the same build parameters and scan patterns for both the part and the supports.

Scan Patterns

Build the calibration parts with the scan patterns as shown in the following figures. (For Assumed Strain simulations, only scan pattern 3 is needed.)

- Scan pattern 1: bi-directional scan with 0° starting angle and 0° layer rotation angle, scan line is either 0° or 180°. See Figure 5 (p. 10).
- Scan pattern 2: bi-directional scan with 90° starting angle and 0° layer rotation angle, scan line is either 90° or 270°. See Figure 6 (p. 10)
- Scan pattern 3: use the scan pattern that you are intending to use for building real components. In this guide we use a rotating stripe scan pattern with a 0° starting angle and a 67° rotation angle. See Figure 7 (p. 11)
- There should be no extra scans such as contour scan, up-skin and down-skin, shrinkage factor, etc.

Figure 5: Scan pattern 1 (0°, 0°)

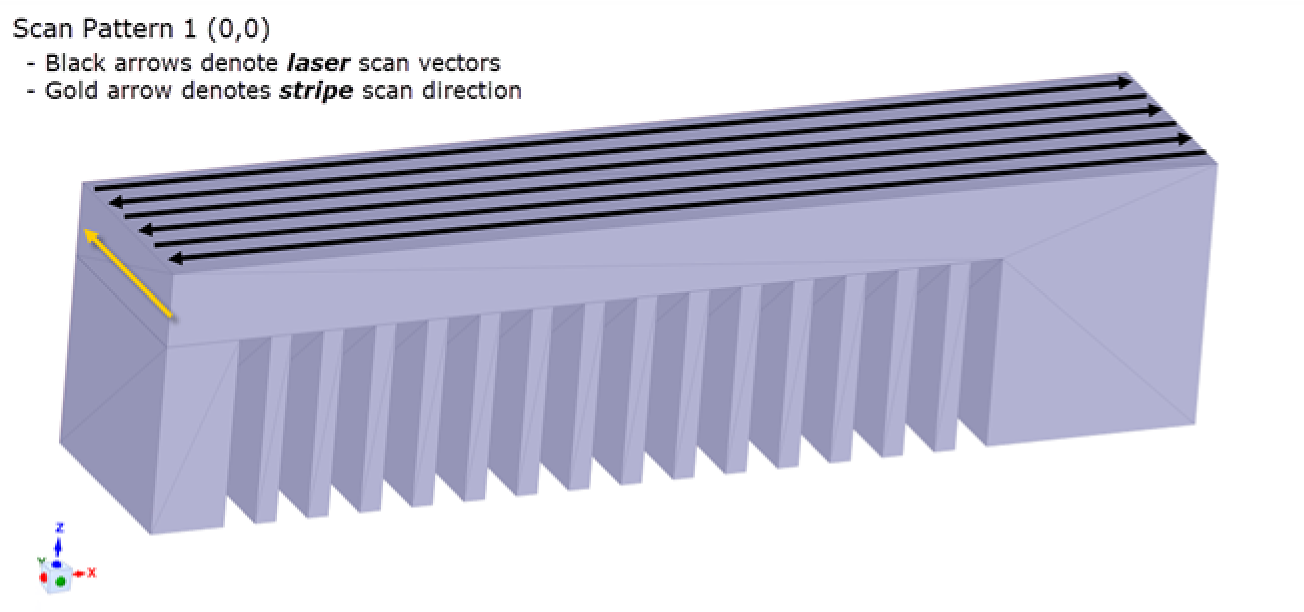


Figure 6: Scan pattern 2 (90°, 0°)

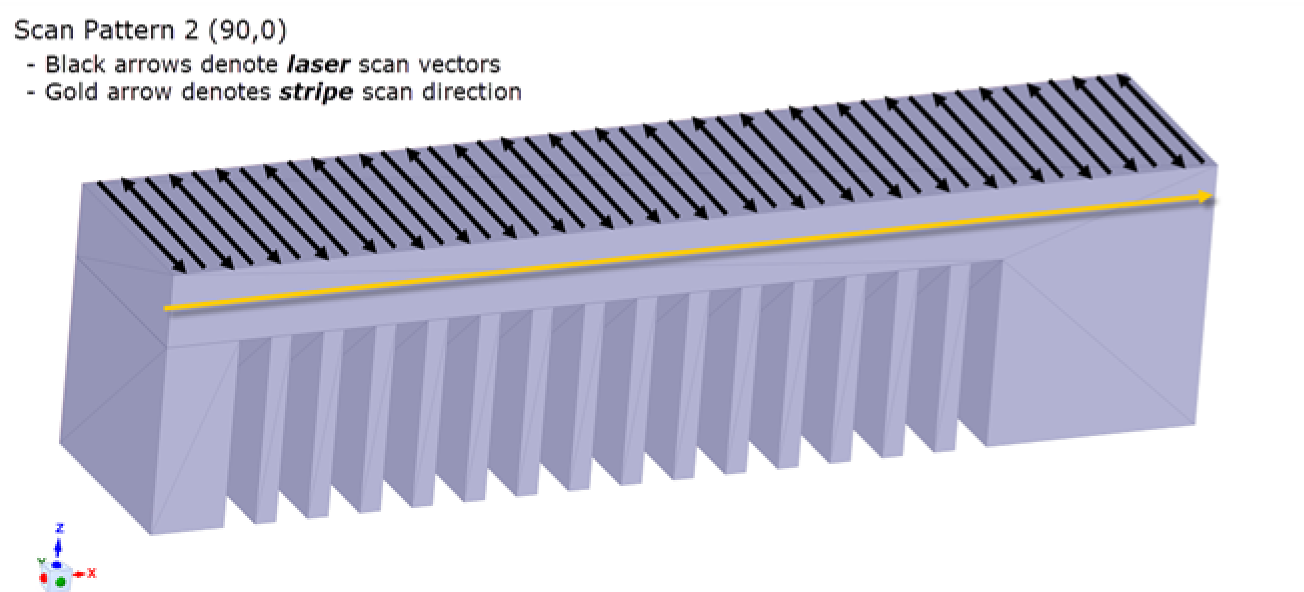
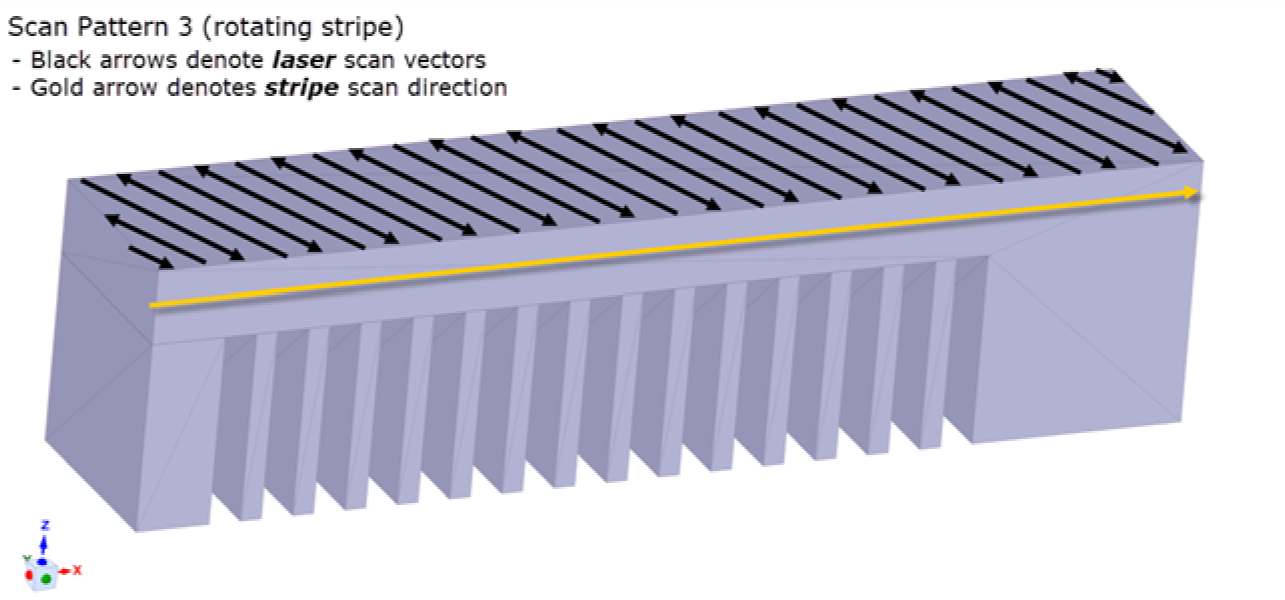


Figure 7: Scan pattern 3 (rotating stripe)



Important:

Pay attention to the legend in Figure 5 (p. 10) and Figure 6 (p. 10). The angles refer to the direction of the laser, not the stripe direction. The X-axis in this guide always runs parallel to the length of the cantilever. Should your machine use a different coordinate system, make sure that scan pattern 1 (0°, 0°) results in the laser scanning parallel to the length of the cantilever. In order to achieve this, it may be necessary to set the stripe width to the length of the cantilever (50 mm) or more.

For scan pattern 2 (90°, 0°), the stripe width may need to be set to the width of the cantilever (10 mm) or more.

Taking Distortion Measurements

Measurement Locations

Measurement locations are shown in the following figures.

- Measurement A is along the center line of the cantilevered edge face (Y=5, X=0 mm) before cutting off the support, as shown in Figure 8 (p. 13). This is the default measurement location.
- Measurement B is along the center line on the top surface of the cantilever beam (Y=5 mm, Z=12.5 mm) after cutting off the support, as shown in Figure 9 (p. 14). This is an optional measurement location.

Figure 8: Measurement location A

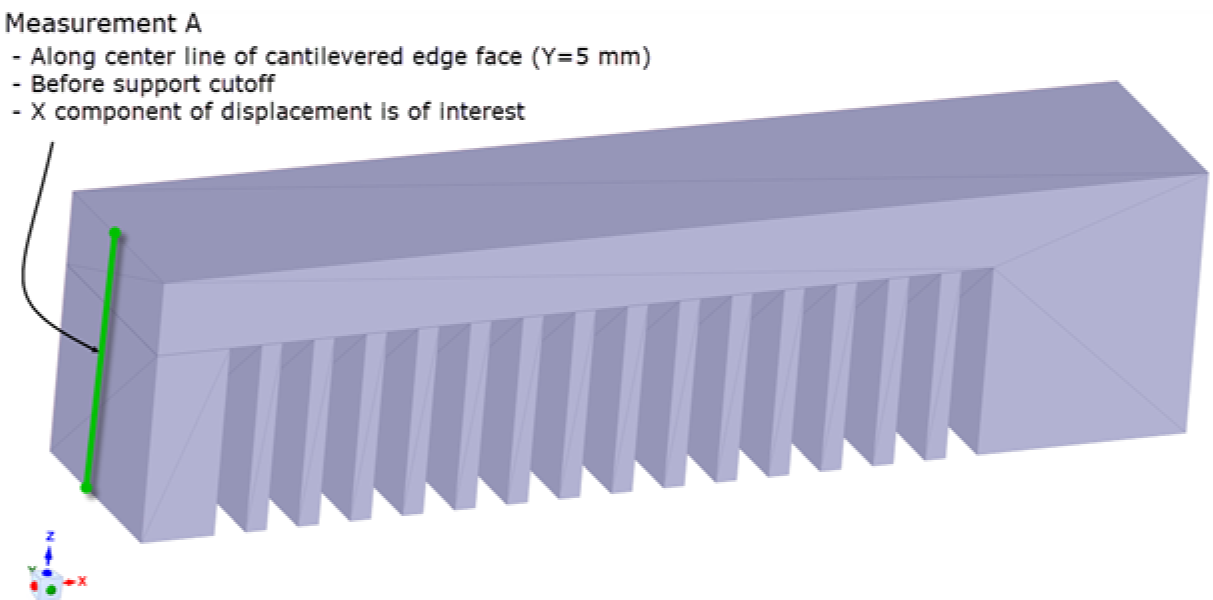
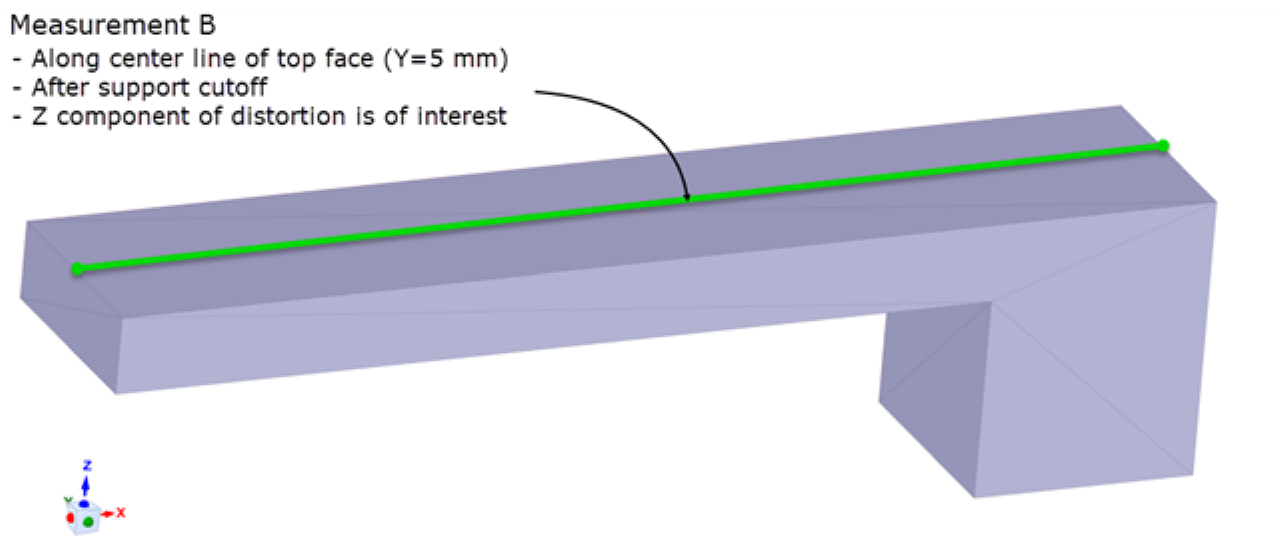


Figure 9: Measurement location B



Our experience has shown that measurement A may be a little difficult to measure. This is why we provide an alternative measurement location, B. Measurement A is usually more sensitive to SSF, however.

If you use a different geometry instead of the cantilever beam, choose one measurable location of interest based on the geometry to perform the calibration.

Measurement Methods

Several measurement methods are available and described below. Choose a measurement technique with the best resolution available.

CMM

If using a Coordinate Measurement Method (CMM), measure many points in a line along the chosen surface of the cantilever beam. Find the maximum deflection for the measurement location(s).

- The maximum X-deflection for measurement A (see Figure 8 (p. 13)) will generally occur at the interface between the beam and the supports, but we recommend comparing measurements along the height.
- The maximum Z-deflection for measurement B (see Figure 9 (p. 14)) will generally occur at the cantilevered end of the beam, but we recommend comparing measurements across the top surface.

Record the value of the dimensions on the spreadsheet provided by ANSYS.

Laser Scanner

If using a laser scanner, point cloud or scanned STL file can be obtained. Measure distortion at the X and Z locations of interest.

Caliper/Micrometer and a Digital Height Gage

If using a caliper/micrometer, we recommend using calipers with fine detail extensions and a digital height gage to mark the height. Measure the dimension of the cantilever beam at the location of interest.

This measurement technique is less accurate than the other methods and may result in inaccurate distortion, SSF, and ASC values. Therefore, this is the least preferred measurement method.

As a last resort, if you do not have a digital height gage, you may want to consider modifying the .stl file to include detents at the location of interest and then use this modified geometry in your simulations.

Running the Simulations

In Additive Print, keep the following settings consistent for all simulations:

- Cantilever beam part (*Cantilever_ANSYS_part.stl*)
- Cantilever beam support (*Cantilever_ANSYS_support.stl*)
- Voxel size: 0.25 mm (This is a suggested value, it can be modified but should be kept consistent throughout all simulations. We recommend you use the voxel size that you will be using for your own part.)
- Material properties, either from an ANSYS-predefined material or your customized material
- Process parameters (needed for Scan Pattern and Thermal Strain simulations)

Use the default output options for measurement A. For measurement B, choose "Displacement after cutoff" and specify "Support-only Cutoff" for Cutoff Mode and "Instantaneous" for Cutoff Method.

Additive Print allows you to prepare multiple simulations and queue them up to automatically run one after another.

Simulations with the First Two Scan Patterns

Scan Pattern/Thermal Strain:

- Start with the default SSF_0= 1
- Start with default ASC_0 (1.5, 0.5, 1)
- Scan pattern 1 – use 0° starting angle and 0° layer rotation angle
- Scan pattern 2 – use 90° starting angle and 0° layer rotation angle

Simulations with the Third Scan Pattern (Fine-tuning Step)

Assumed Strain:

- For both linear elastic and J2 plasticity, start with the SSF_0= 1

Scan Pattern/Thermal Strain:

- For both linear elastic and J2 plasticity, start with the calibrated SSF
- Use the calibrated ASCs

- Machine Configuration - Use the scan pattern angles you used to build the third part (such as scan pattern 3 as shown in Figure 7 (p. 11)).

Extracting Distortion Data - Measurement A

For simulation of measurement A, use the **On-plate residual stress/distortion** results to extract the directional component of displacement at the ends of the cantilever beam at the location of interest, Measurement A. Use either the ANSYS viewer in Additive Print to view the results (hover the mouse over the location of interest to get the displacement) or export the files to view in another viewer application.

Extracting Distortion Data - Measurement B

For simulation of measurement B, use the **Displacement after cutoff** > **Support-only Cutoff** > **Instantaneous** results to extract the displacement in the Z direction along measurement B.

Note:

Locations of data extraction from the simulations should match the measurement locations.

Figure 10: Selected points on support (left) and on cantilever beam part (right) along measurement A

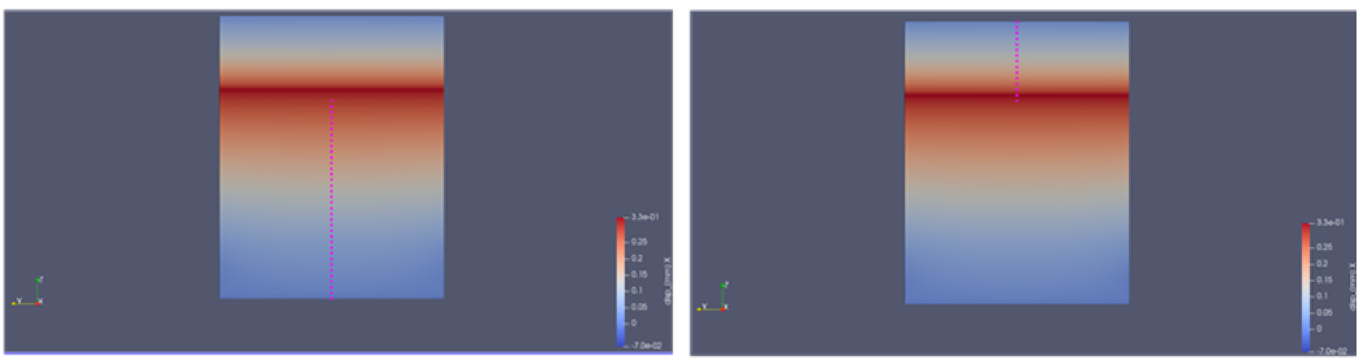
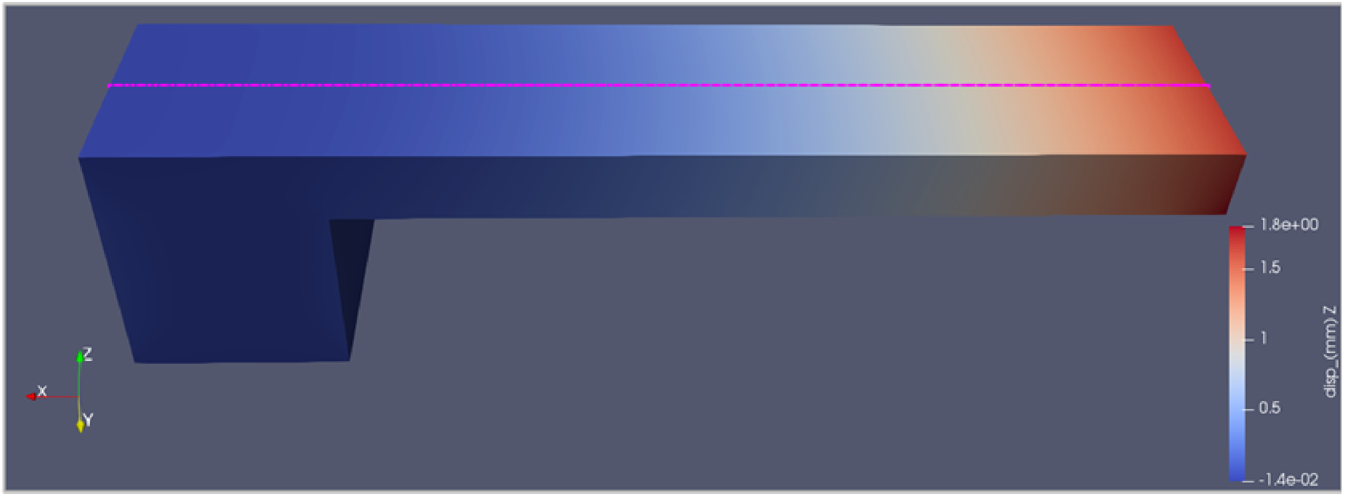


Figure 11: Selected points on cantilever beam along measurement B after cutoff



The data point coordinates at the locations of interest, as shown in Figures 8 (p. 13) and 9 (p. 14), are:

- Measurement A: (0, 5, 8.5) to (0, 5 ,12.5) Use X-displacement value
- Measurement B: (0, 5, 12.5) to (50, 5, 12.5) Use Z-displacement value

The distortion on measurement A is the maximum X-displacement value.

The distortion on measurement B is the maximum Z-displacement value at X = 50 mm.

Paraview is an open-source, multi-platform data analysis and visualization application. Within Paraview, extract the distortion data by doing the following:

Open the appropriate files and make it active.

Edit > Find Data...

Figure 12: Example of how to use Paraview to find displacement value for measurement B

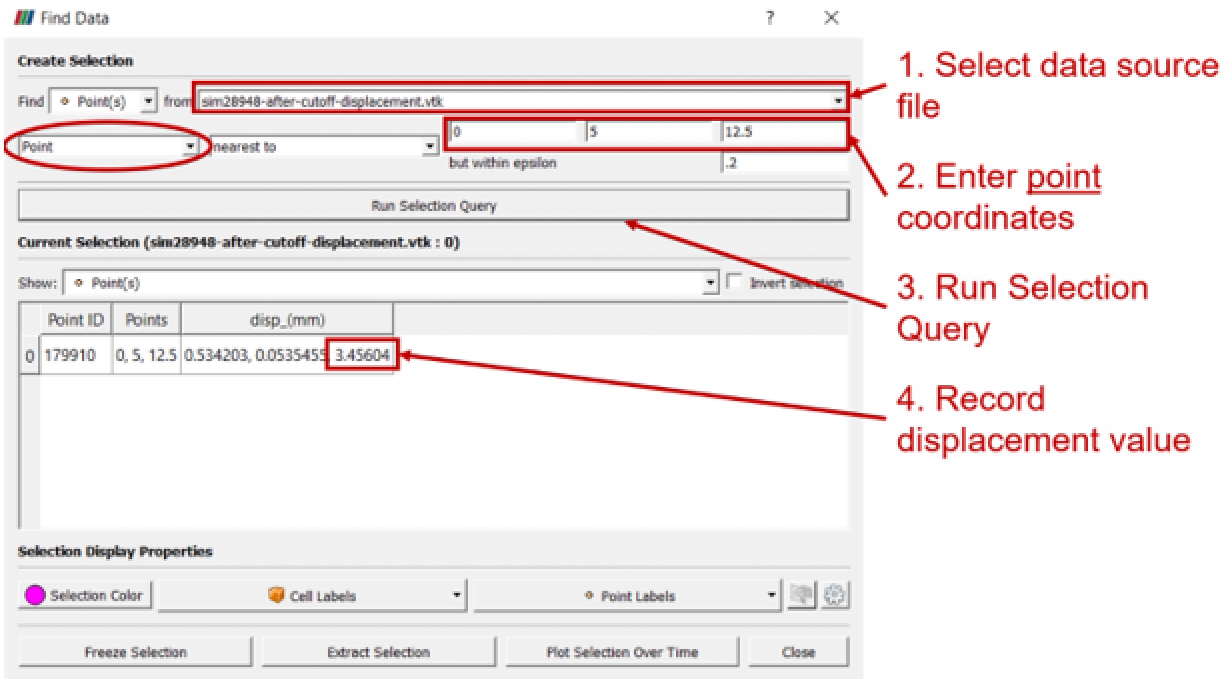
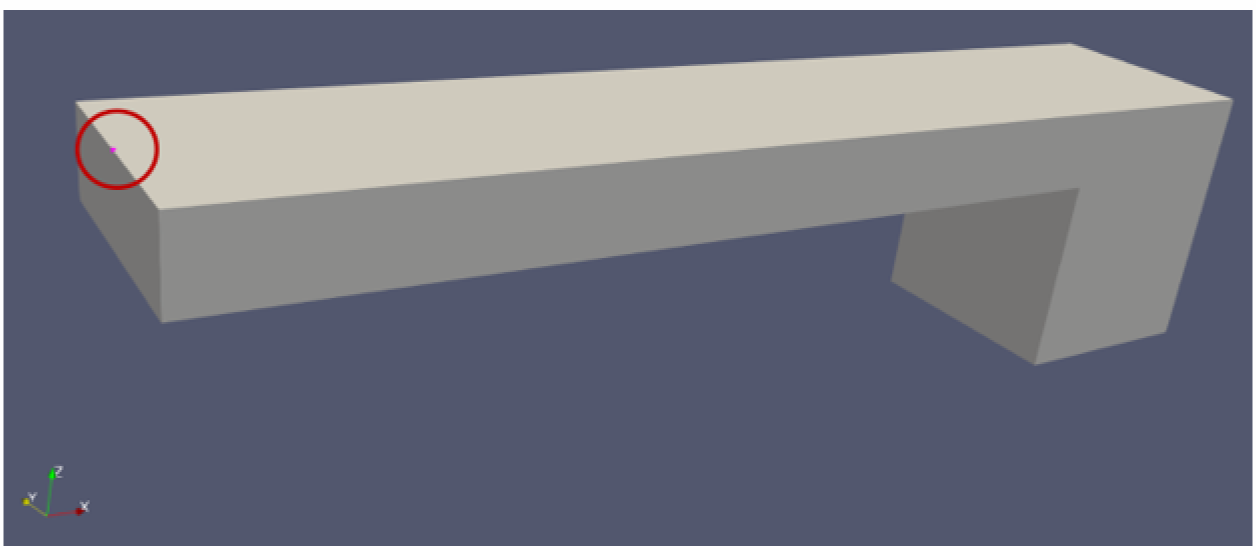
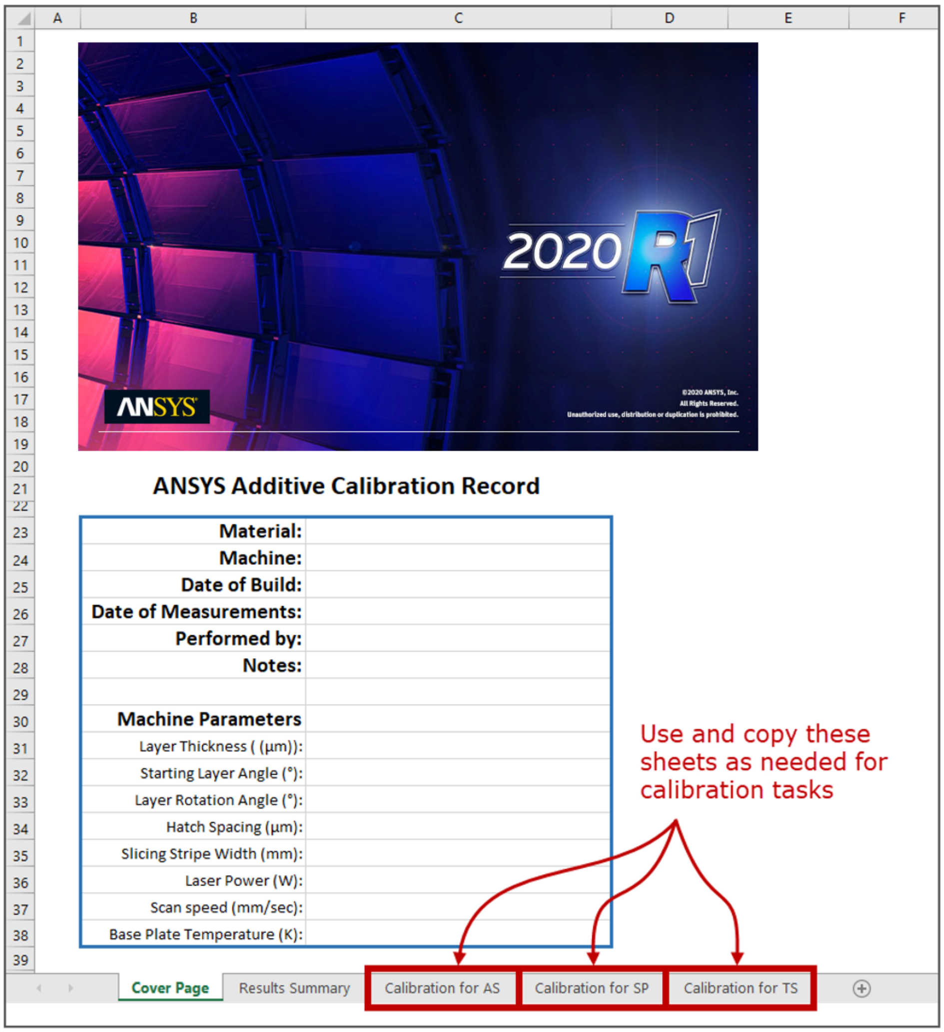


Figure 13: Point highlighted after using the "Find Data" query

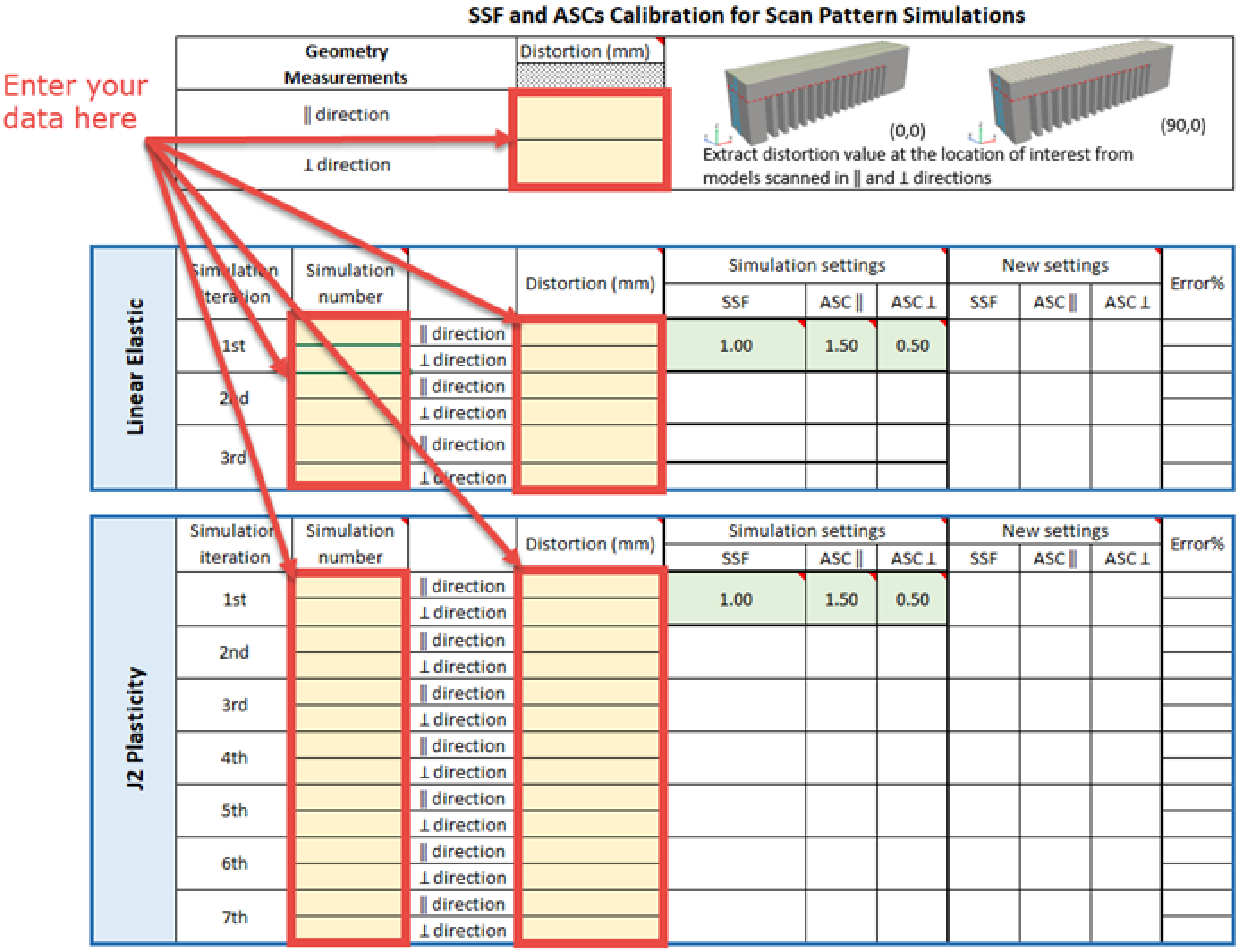


Using the Spreadsheet to Calculate SSF and ASCs

An easy-to-use, customized spreadsheet (.xlsx file) is available to calculate the Strain Scaling Factor (SSF) and the Anisotropic Strain Coefficients (ASCs). (The spreadsheet is available for download here.) Tabs at the bottom of the spreadsheet (**Calibration for AS**, **Calibration for SP**, and **Calibration for TS**) represent the three different simulation types.



The sheets are designed so that you enter your own data in the colored-filled cells and the corresponding values for SSF and ASCs will automatically be calculated based on formulas locked into the spreadsheet. Sample values are included in the colored cells just as an example, so the first thing to do is clear the sample data.

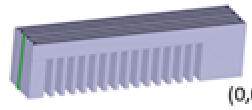
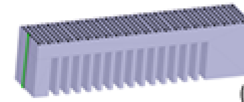


1. **Run first calibration set to determine an initial set of factors (for each simulation type and stress mode combination)**

   For a chosen combination of simulation type and stress mode, run simulations of the calibration part in Additive Print. Use the spreadsheet to calculate factors.

   a. Run a simulation of the calibration part using *default SSF and ASCs*.

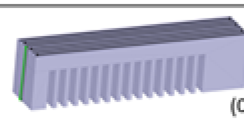
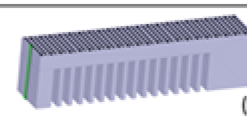
SSF and ASCs Calibration for Scan Pattern Simulations

Geometry Measurements	Distortion (mm)	
‖ direction	1.342	 (0,0)  (90,0)
⊥ direction	0.892	Extract distortion value at the location of interest from models built with scan patterns 1 and 2 (‖ and ⊥)

					Simulation settings			New settings			
	Simulation iteration	Simulation number		Distortion (mm)	SSF	ASC ‖	ASC ⊥	SSF	ASC ‖	ASC ⊥	Error%
Linear Elastic	1st		‖ direction	3.456	1.00	1.50	0.50	0.43	1.20	0.80	157.5%
			⊥ direction	1.786							100.2%
	2nd		‖ direction								
			⊥ direction								
	3rd		‖ direction								
			⊥ direction								

b. Calculate new SSF and ASCs using simulation distortion data compared to measured distortion data from the calibration part. (This is done automatically with formulas built into the spreadsheet.)

SSF and ASCs Calibration for Scan Pattern Simulations

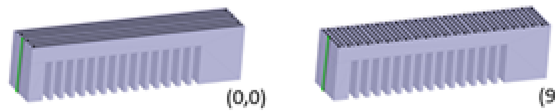
Geometry Measurements	Distortion (mm)	
‖ direction	1.342	 (0,0)  (90,0)
⊥ direction	0.892	Extract distortion value at the location of interest from models built with scan patterns 1 and 2 (‖ and ⊥)

					Simulation settings			New settings			
	Simulation iteration	Simulation number		Distortion (mm)	SSF	ASC ‖	ASC ⊥	SSF	ASC ‖	ASC ⊥	Error%
Linear Elastic	1st		‖ direction	3.456	1.00	1.50	0.50	0.43	1.20	0.80	157.5%
			⊥ direction	1.786							100.2%
	2nd		‖ direction	1.678	0.43	1.20	0.80	0.34	1.20	0.80	25.0%
			⊥ direction	1.121							25.7%
	3rd		‖ direction		0.34	1.20	0.80				
			⊥ direction								

c. Run simulations using calculated SSF and ASCs, and then iterate until the new SSF and ASCs converge to an acceptable level of error between measured and simulated distortion.

SSF and ASCs Calibration for Scan Pattern Simulations

Geometry Measurements	Distortion (mm)
‖ direction	1.342
⊥ direction	0.892



Extract distortion value at the location of interest from models built with scan patterns 1 and 2 (‖ and ⊥)

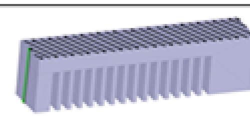
	Simulation iteration	Simulation number		Distortion (mm)	Simulation settings SSF	Simulation settings ASC ‖	Simulation settings ASC ⊥	New settings SSF	New settings ASC ‖	New settings ASC ⊥	Error%
Linear Elastic	1st		‖ direction	3.456	1.00	1.50	0.50	0.43	1.20	0.80	157.5%
			⊥ direction	1.786							100.2%
	2nd		‖ direction	1.678	0.43	1.20	0.80	0.34	1.20	0.80	25.0%
			⊥ direction	1.121							25.7%
	3rd		‖ direction	1.36	0.34	1.20	0.80	0.42	1.19	0.81	1.3%
			⊥ direction	0.90							0.7%

2. **Run fine-tuning calibration step with a different scan pattern**

   a. Run a simulation of the calibration part using a rotating stripe scan pattern and the *calibrated SSF and ASCs*.

SSF and ASCs Additional Calibration for Scan Pattern Simulations

Geometry Measurements	Distortion (mm)
Rotating stripe scan pattern (or user-customized)	0.46

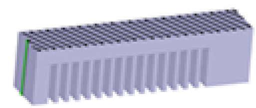


Extract distortion value at the location of interest from models built with third scan pattern (rotating stripe)

	Simulation iteration	Simulation number	direction	Distortion (mm)	Simulation settings SSF	Simulation settings ASC ‖	Simulation settings ASC ⊥	New settings SSF	New settings ASC ‖	New settings ASC ⊥	Error%
Linear Elastic	1st		rotating	0.758	0.34	1.20	0.80	0.21	1.20	0.80	63.4%
	2nd		rotating		0.21	1.20	0.80				

   b. Run simulations using the newly-calculated SSF and then iterate until the new SSF converges to an acceptable level of error between measured and simulated distortion.

SSF and ASCs Additional Calibration for Scan Pattern Simulations

Geometry Measurements	Distortion (mm)	
Rotating stripe scan pattern (or user-customized)	0.46	 Extract distortion value at the location of interest from models built with third scan pattern (rotating stripe)

	Simulation iteration	Simulation number	direction	Distortion (mm)	Simulation settings			New settings			Error%
					SSF	ASC ∥	ASC ⊥	SSF	ASC ∥	ASC ⊥	
Linear Elastic	1st		rotating	0.758	0.34	1.20	0.80	0.21	1.20	0.80	63.4%
	2nd		rotating	0.47	0.21	1.20	0.80	0.21	1.20	0.80	0.2%

c. Record the final SSF and ASCs in a table such as the one shown in Table 1: Complete matrix of SSF and ASCs (p. 6).

Other Considerations

The distortion values seen in the spreadsheets are for demonstration purposes only. Distortion values will vary based on material, machine, and build parameters.

You will need to copy calibration sheets for other simulations.

If you use both locations A and B (assuming that both values are useful and measurable), use the average value of SSF and ASCs obtained from the spreadsheet after the simulations. Therefore:

$$SSF_{cantilever\_beam}=(SSF_A+SSF_B)/2$$

$$ASC_{cantilever\_beam\|}=(ASC_{A\|}+ASC_{B\|})/2$$

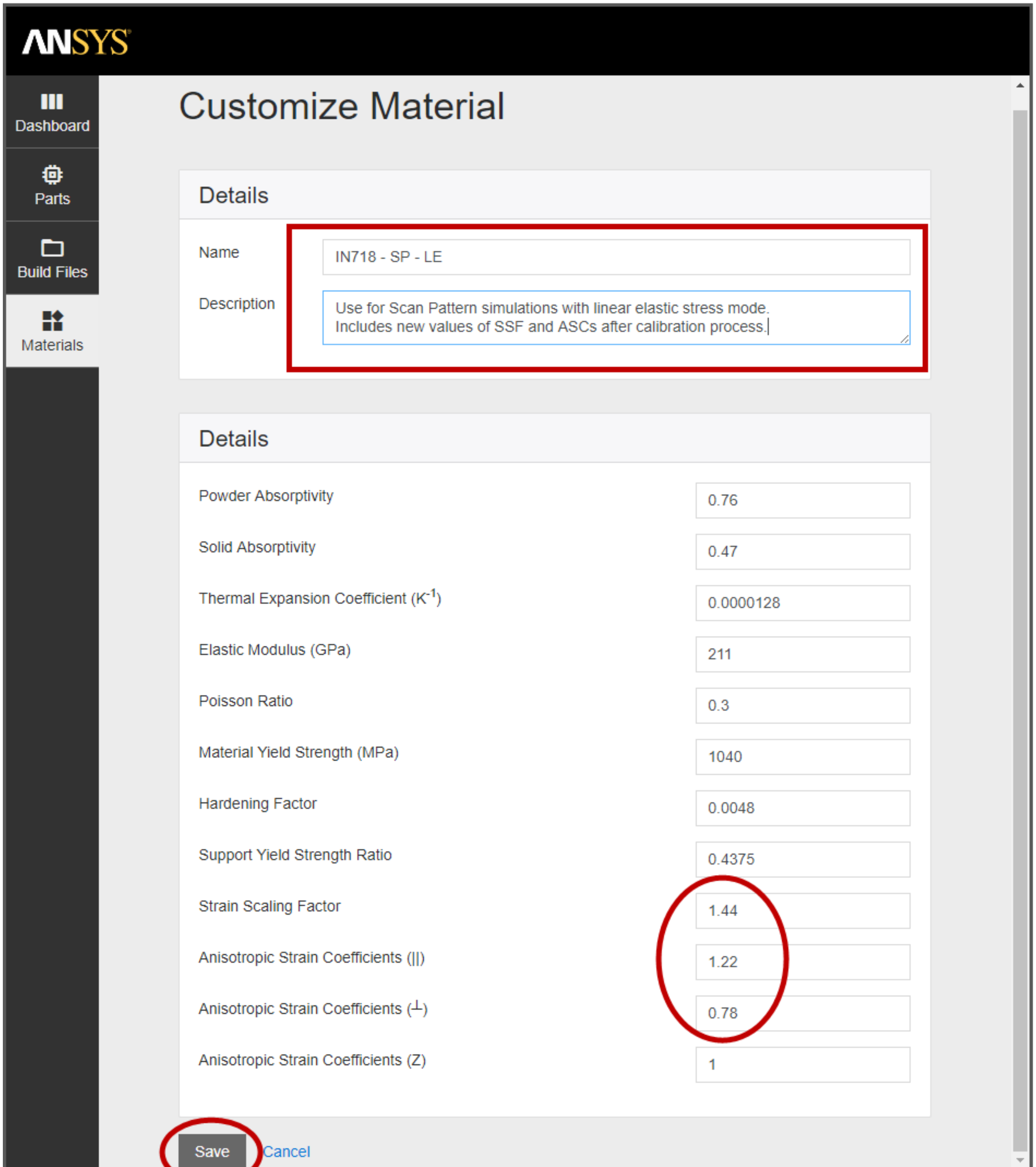
$$ASC_{cantilever\_beam\perp}=(ASC_{A\perp}+ASC_{B\perp})/2$$

Saving Your Final Results as Custom Materials

The calibration process is complete when you have obtained values for SSF and ASCs that are within an acceptable level of error between measured and simulated distortion. Because the goals of every company and the design of every manufactured part are unique, it is up to you to decide what is an acceptable level of error. Record the final values in the Results Summary sheet in the spreadsheet. (The Results Summary sheet is the same as Table 1 shown in this guide.) Then use those new values of SSF and ASCs for all your simulations in Additive Print for that machine and material.

Within Additive Print, we recommend you save the final SSF and ASCs by creating customized materials for each material/simulation type/stress mode combination.

In the Materials library, select your material and then click Customize. This brings up an edit panel where you can change the SSF and ASC values to the final calibrated values. Then be sure to select the appropriate custom material when performing future simulations.


Customize Material
Details
Name
IN718 - SP - LE
Description
Use for Scan Pattern simulations with linear elastic stress mode.
Includes new values of SSF and ASCs after calibration process.
Details
Powder Absorptivity
0.76
Solid Absorptivity
0.47
Thermal Expansion Coefficient (K-1)
0.0000128
Elastic Modulus (GPa)
211
Poisson Ratio
0.3
Material Yield Strength (MPa)
1040
Hardening Factor
0.0048
Support Yield Strength Ratio
0.4375
Strain Scaling Factor
1.44
Anisotropic Strain Coefficients (||)
1.22
Anisotropic Strain Coefficients (⊥)
0.78
Anisotropic Strain Coefficients (Z)
1
Save
Cancel
Dashboard
Parts
Build Files
Materials

Appendix A. Equations for Calculating SSF and ASCs

The equations used in the ANSYS-provided spreadsheet (p. 21) for calculating the Strain Scaling Factor (SSF) and Anisotropic Strain Coefficients (ASCs) are shown here for reference.

The following SSF and ASC equation topics are available:

For an overview of the calculation process, see Process Flow for the SSF and ASCs Calculations (p. 33).

Nomenclature

The equations in this appendix use the following standard nomenclature:

Table 2: Variables

Variable	Meaning
δe	Experimental distortion
δs	Simulation distortion
r	Ratio

Table 3: Subscripts

Subscript	Meaning
$\|\|$	Parallel to the scan direction
$\perp$	Perpendicular to the scan direction
$n-1$	Setting before the most recent iteration
n	Setting of the most recent iteration
$n+1$	Setting for the next iteration
0, 1, 2, ...	iteration 1, iteration 2, iteration 3, …
m	Modified version

Linear Elastic Stress Mode Calculations

Assumed Strain SSF

$$SSF_{new}=\frac{\delta e}{\delta s}\bullet SSF_{old}$$

Scan Pattern / Thermal Strain SSF

$$SSF_{new}=\frac{\delta e_{||}+\delta e_{\perp}}{\delta s_{||}+\delta s_{\perp}}\bullet SSF_{old}$$

Scan Pattern / Thermal Strain ASCs

$$ASC_{||}=\frac{2}{\left(1+\frac{\delta e_{\perp}}{\delta e_{||}}\right)}$$

$$ASC_{\perp}=2-ASC_{||}$$

Plasticity Stress Mode Calculations

Follow these steps to perform the plasticity stress mode calculations:

Step 1: Set the First Iteration of Simulations

Set the first iteration of simulations using these defaults:

- Assumed Strain mode: $SSF_0=1$
- Scan Pattern / Thermal Strain mode: $SSF_0=1$, $ASC_{||0}=1.5$, and $ASC_{\perp 0}=0.5$

For Assumed Strain mode, extract target distortion value δs_0.

For Scan Pattern / Thermal Strain mode, extract target distortion value $\delta s_{0||}$ from one simulation, and $\delta s_{0\perp}$ from a second simulation.

Step 2: Calculate the New SSF and ASCs

Calculate the new SSF and ASCs after the first iteration:

Assumed Strain

$$SSF_1=(\delta e/\delta s_0)SSF_0$$

Scan Pattern / Thermal Strain

Calculate the average value of distortion in the parallel and perpendicular directions after the first distortion:

$$avg(\delta)=\frac{\delta_{||}+\delta_{\perp}}{2}$$

Calculate SSF and ASC in the second iteration by:

$$SSF_1 = SSF_0 \frac{avg(\delta e)}{avg(\delta s_0)}$$

$$ASC_{||1} = (2 - ASC_{||0})\left(\frac{\delta e_{||} + \delta s_{\perp}}{\delta e_{\perp} + \delta s_{||}} - 1\right) + ASC_{||0}$$

Step 3: Determine Whether the New SSF Is < 1 or $\geq$ 1

If the suggested new SSF_1 is less than 1, set SSF_{1m} = 0.002 and run the simulation to extract δs_1.

If the suggested new SSF_1 is grater than or equal to 1, set SSF_{1m} = SSF_1 and run the simulation to extract δs_1.

Step 4: Perform Linear Interpolation Between Iterations 1 and 2

Perform linear interpolation between the iteration 1 (default value) and iteration 2 to extract SSF_2, ASC_2, and the values for the subsequent iterations.

For SSF_{1m} = 0.002 (SSF_1 < 1)

1. $SSF_2 = \frac{(\delta e - \delta s_0)(SSF_1 - SSF_0)}{(\delta s_1 - \delta s_0)} + SSF_0$

2. Determine whether $avg(\delta s_1) < avg(\delta e) < avg(\delta s_2)$.

   If *Yes*:

   $$SSF_{n+1} = \frac{(\delta e - \delta s_1)(SSF_n - SSF_1)}{(\delta s_1 - \delta s_0)} + SSF_1, where\, n \geq 2$$

   If *No*:

   $$SSF_{n+1} = \frac{(\delta e - \delta s_0)(SSF_n - SSF_0)}{(\delta s_n - \delta s_0)} + SSF_0, where\, n \geq 2$$

For SSF_{1m} = SSF_1 (SSF1 $\geq$ 1)

$$SSF_{n+1} = \frac{(\delta e - \delta s_{n-1})(SSF_n - SSF_{n-1})}{(\delta s_n - \delta s_{n-1})} + SSF_{n-1}, where\, n \geq 1$$

For Both Cases

$$r = \frac{\delta s_{||}}{\delta_{\perp}} \qquad r_e = \frac{\delta e_{||}}{\delta e_{\perp}}$$

$$ASC_{||n+1} = \frac{(r_e - r_{n-1})(ASC_{||n} - ASC_{||n-1})}{(r_n - r_{n-1})} + ASC_{||n-1}$$

$$ASC_{\perp n+1} = 2 - ASC_{||n+1}$$

Step 5: Calculate the Relative Error

Calculate the relative error $\frac{\left|\delta s_{||n} - \delta e_{||}\right|}{\delta e_{||}}$, where n≥1 and $\frac{\left|\delta s_{\perp n} - \delta e\perp\right|}{\delta e\perp}$, where n≥1.

Determine whether the error exceeds your tolerance.

If *Yes*:

End the calibration program.

If *No*:

Go back to the iteration.

Process Flow for the SSF and ASCs Calculations