

MULTIAXIAL EXPERIMENTAL DETERMINATION OF FAILURE OF COMPOSITE
MATERIALS THROUGH DIGITAL IMAGE CORRELATION TO
CALIBRATE COMPOSITE FAILURE THEORIES

by

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NOMENCLATURE

x	X coordinate direction relative to the sample when under testing conditions
y	Y coordinate direction relative to the sample when under testing conditions
z	Z rotational coordinate direction relative to the existing x and y directions
F_x	Force in the relative x direction
F_y	Force in the relative y direction
F_{xy}	Moment in the relative z direction
ϵ_{xx}	Strain in the relative x direction
ϵ_{yy}	Strain in the relative y direction
ϵ_{xy}	Strain in the relative z direction
ϕ_M	Equivalent Mises strain measured via DIC
σ_{xx}	Stress in the relative x direction
σ_{yy}	Stress in the relative y direction
τ_{xy}	Shear stress in the relative z direction
σ_1	Maximum normal stress
σ_2	Minimum normal stress
τ_{max}	Maximum shear stress
lbf	Pounds of force
lbf-in	Inch-pounds of moment
V	Volts
mm	Millimeters
in/s ²	Inches per second squared
in/s	Inches per second
psi	Pounds per square inch
ksi	Thousands of pounds per square inch

ABSTRACT

The purpose of this study is to experimentally test uniaxial, biaxial, and triaxial fiberglass laminates to failure via multiaxial testing. These tests provided force and strain data that can be used to calibrate existing composite failure theories to better predict failure of composite materials. Multiaxial testing consisted of loading fiberglass coupon samples of two different notch geometries, with each notch geometry repeating four specific testing directions.

The force and strain data from each test were recorded, with force data being extracted through load cells, and strain data being recorded through Digital Image Correlation (DIC). Both strain and force data consisted of three directional components each. The three directional strain components from each test were used as three-dimensional coordinates in a scatter plot for each laminate. These plots showed the relationship of how different combinations of strain directions result in failure of a given composite. Recorded directional force data at the point of failure for each test will provide a critical basis for reconstructing testing conditions in Finite Element Analysis (FEA) to calculate the actual experienced stresses in the coupon. Calculated stresses and measured strains will be used as a foundation for any future calibration of failure theories for composite materials.

The resulting scatter plots displayed patterns that represented understandings of the limits of strain combinations that result in failure of uniaxial, biaxial, and triaxial layups, and how those patterns may grant insight into how the combinations of strains that result in failure can be predicted through the knowledge of failure of the laminae that make up the laminate.

INTRODUCTION

This research consisted of experimental laboratory work to provide large quantities of data on composite materials according to the testing list provided by Sandia National Labs (SNL). This data was measured and recorded through Digital Image Correlation (DIC) and load cells. The three main laboratory testing equipment used to extract this data were: an in-house In-Plane Loader (IPL), a GOM DIC system, and the Instron 8562. Before the testing of fiberglass samples began, the overall testing methodology was verified through copper samples. The resulting copper data collected was compared to published values for validation of the testing setup. Following the accurate resulting data from the copper samples through use of the IPL and DIC, fiberglass testing according to the testing list was fulfilled. Analysis of the data resulting from all fiberglass tests was performed, including plotting of resulting directional strain combinations that led to failure of a sample, and the combination of resulting forces at the time of failure.

Background of Research

A comprehensive testing list was provided by SNL. The list was comprised of eight separate testing directions that mimicked virtual Finite Element Analysis (FEA) simulations previously performed. This was done to allow for the experimental replication of these simulations to gather large amounts of multiaxial loading failure data that could eventually be used to calibrate existing composite failure theories to allow for the better designing of composite structures. This testing table was first revised to allow for testing magnitudes to be performed within all the machines' precision and measuring capabilities. Due to the custom nature of the IPL, its capabilities would be assessed firsthand to understand its operational

and behavioral characteristics prior to data collection. Standard and appropriate use of the DIC and Instron would be carried out during testing.

Experimental Testing

Prior to testing composite samples, testing of copper samples with known material properties occurred. Copper coupons were machined to be pulled in tension and tested in the IPL. Strain and force data were recorded throughout the duration of the tensile test to plot stress-strain curves, where the elastic modulus and yield strength of the resulting curve was compared to the documented copper properties. Once it was verified that the testing methodology produced accurate values, testing of composite samples began. Fiberglass testing prompted the need for the fabrication of fiberglass coupons. All fiberglass coupons are four plies with the same resin system. Three different layups of fiberglass were chosen for testing: uniaxial, biaxial, and triaxial laminates. Once the samples were cut to shape, painted to be measured by the DIC, and tabbed to get even clamping force in the IPL grips, the coupons were tested. All three layups were tested across 8 different testing directions multiple times to get good, repeated data points. Once all tests were done, analysis of the resulting data began.

Analysis Process

After testing was completed and data was compiled, each test was carefully and manually analyzed. Data inspection began with the DIC recordings of strain calculations and recorded forces over a tests' duration. The force and strain data were exported and plotted against one another in Excel to determine a point of failure during a test. Once a point of failure was determined, directional strain data and force data was recorded at that instance of failure. This data was plotted in a 3D scatter plot in MATLAB to help visualize

the change in strain combinations that result in failure of a composite for a particular layup. Two scatter plots were made for each of the three layups, one of the force combinations, and the other of the strain combinations.

BACKGROUND OF RESEARCH

Numerous theories exist to attempt to predict failure in composites, all of which require experimental data for calibration. The laboratory tests conducted in this study were performed according to an explicit testing list given by SNL. The list described eight separate testing scenarios with specific ratios of x , y , and z boundary displacements applied to the coupon for fiberglass samples to be pulled in. These outlined tests mimic the exact displacement conditions performed in FEA by a former student in the Composites Technology Research Group at Montana State University. The tests using IPL, DIC, and Instron were carried out according to these instructions.

Failure Background

Primary failure within composites is often through first ply failure (FPF) [1, 32]. This typically occurs within the matrix of a composite due to the tensile strength of the fibers being far greater than the transverse or shear strength within the matrix [1]. Failure of all tested composites was determined around FPF in this published data.

To understand and visualize the instances of FPF, failure envelopes are plotted to show the predicted conditions in which a laminate will begin to fail through combinations of different stresses or strains (see Figure 1). According to the failure envelopes, any combinations of strains or stresses that lie within the bounds of the curve should not result in failure within a laminate. Several failure mechanisms exist across composites [20, 29] with most common failure criteria being the maximum strain criterion and the maximum stress criterion [15, 31]. The maximum strain and maximum stress criteria are relatively simplistic in computation, permitting use for quick estimations [18].

While failure envelopes display an understandable criteria of failure across a complex set of conditions, their lack of accuracy allows for disregarding of their face-value credibility.

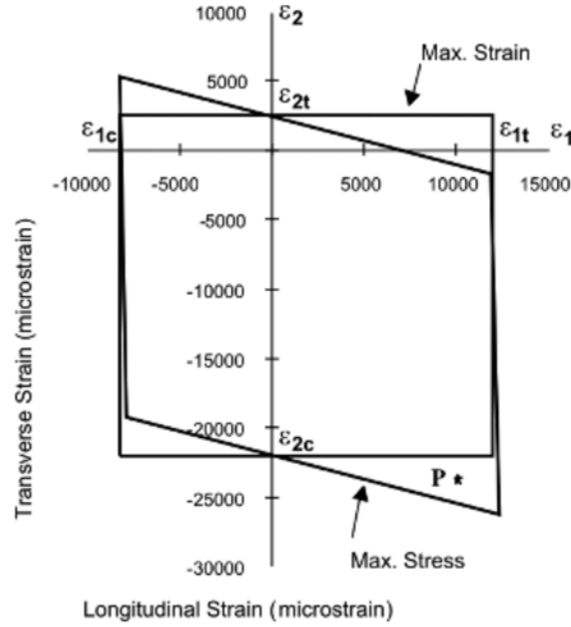


Figure 1: Example failure envelope showing the overlapping conditions of failure in composites as predicted by the maximum stress and maximum strain criterion [1].

Additionally, failure envelopes differ in predicted results depending on the applied failure criteria. This leads to the lack of accurate prediction of laminates of complex loading conditions. Experimental data has shown to accurately align with parts of specific failure envelopes (see Figure 2) [12, 16, 17, 29].

Other complex failure criteria exist in effort to better the prediction of failures in composites. In 1973, Z. Hashin and A. Rotem established a failure mechanism based on failure of the fibers, and another based on the failure of the matrix [11, 19]. Additionally, A. Puck and H. Schurmann introduce an angle of fracture plane within their refined failure mechanisms [24, 25].

From the advancements in composites failure mechanisms made by Z. Hashin and A. Puck, further advancements were made by NASA for fiber reinforced polymer laminates in their LaRC02 mechanism [5]. Like Hashin's failure mechanisms, LaRC02 predicts matrix and fiber failures but accomplishes this without the requirement for curve fitting parameters [5].

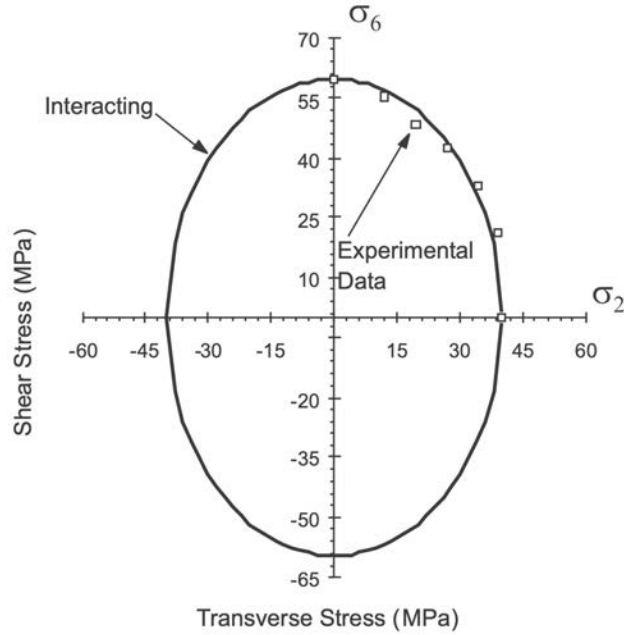


Figure 2: Experimental data aligning with the transverse and shear stress failure envelope [1].

This was then gradually refined through the iterations of LaRC03 [4] and LaRC04 [23].

The data published in this study displays experimentally determined failure envelopes from ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strain values occurring at the location and time of FPF across uniaxial, biaxial, and triaxial layups. Data is plotted in strain and force 3D scatter plots. Coordinates for the strain scatter plots are ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} as the X, Y, and Z points, respectively. Similarly, the coordinates for the force scatter plots are F_x , F_y , F_{xy} as the X, Y, and Z points, respectively. F_{xy} represents a moment about the z axis instead of M_z due to hardware compatibility constraints. The purpose behind this is to provide 3D directional strain failure envelopes along with force data associated with each test. The strain data is used to portray the expected failure envelope of a sample, and the force data can be used to replicate the exact loading conditions in FEA to extract the stresses in every sample. Additionally, trends can be observed across the scatter plots when cross-referencing the three separate layups. These sets of values can then be used to tune existing composite failure theories to better predict the failure of composite materials.

Finite Element Analysis Background

The FEA simulations previously performed granted a look into some basic understandings of how samples of specific geometries would react when under various displacement conditions [7]. These simulations made simplifications, such as overall coupon length and simulated material type. Due to these simplifications, resulting numbers cannot be taken as fact, but instead as a general idea of an outcome of such displacements. To verify any implied behaviors seen in the simulations, experimental work must be performed. The primary data extracted from the simulations were the principal stresses, σ_1 and σ_2 , and the directional stresses at the location of maximum principal stress, σ_{xx} , σ_{yy} , and τ_{xy} . Following the extraction of these values, stress ratios of $\sigma_{yy} / \sigma_{xx}$ and σ_{yy} / τ_{xy} were used to reference experimental and simulation values to one another, as seen in one example in Figure 3.

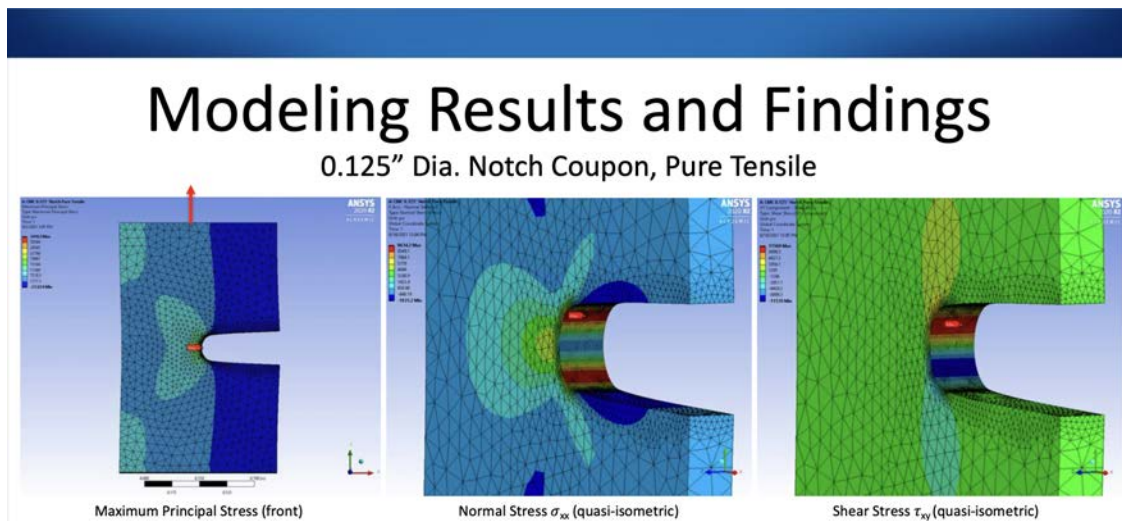


Figure 3: Example FEA simulation by a former student in the Composites Technology Research Group at Montana State University showing the results of a single 0.125 inch diameter notch coupon subjected to exclusively tensile displacement conditions [7].

The FEA simulations consisted of 14 different iterations, consisting of three separate notch geometries. The three notch geometries were: a single notch made 0.125 inches in diameter, a single notch made 2 inches in diameter, and a double notch made 2 inches in

diameter. All notch geometries were made in 1 inch wide virtual material. Both the 0.125 inch single notch and the 2 inch double notch were cut to allow for a minimum coupon width of 0.5 inches at the endpoint of the notches. The analysis of the simulations showed that some tests displayed symmetric or repeated results. With this knowledge, 8 of the 14 tests that were unique were brought together to make a testing list that would be recreated experimentally (see Table 1). These eight tests were created to replicate the FEA simulations in both displacement conditions and notch conditions for all three layups, as well as to invoke a wide variety of failure conditions within the samples. The notch geometries used in testing consisted of the single 0.125 inch diameter notch, and a double 2.00 inch diameter notch. Once all three layups have been tested according to the eight listed conditions an adequate number of times, testing would be complete.

The purpose of the testing list was to invoke a wide variety of failure conditions within a coupon to extract varying resulting strain conditions to help better the understanding of the entire scope of failure. Table 1 outlines tests of varying tensile and shear conditions for uniaxial, biaxial, and triaxial layups of two separate notch geometries to invoke such conditions.

Testing List Revisions

Following the acquisition of the testing list provided by SNL, the magnitudes of the displacement vectors were far too small and precise to be appropriately replicated by the IPL or Instron or observed by the DIC. Table 1 consists of eight 1:1 recreations of the simulated elements done in FEA, comprised of the single 0.125 inch notch and the double 2.00 inch notch from the simulations. While the magnitude of the initial testing directions is identical to the FEA simulations, no meaningful data will result from replicating these experimentally. Not only are the magnitudes far too precise for the involved machines' capabilities, but any samples subject to these displacements will display little, if any, difference to their relaxed

states prior to testing. A new, revised testing plan was necessary that preserves the original testing lists' displacement vectors while increasing the magnitudes to provoke failure in test samples for adequate data collection.

Table 1: Original testing plan given by SNL that recreates eight FEA simulations consisting of directional magnitudes that are too small for the given equipment.

Test	Notch Size	Description	Direction	Magnitude
T1	0.125"	Pure Tensile 1:0	+ Y	Y=0.00075 in
T2	0.125"	Tensile & Rotation	+ Y; + Z	Y=0.0005 in; Z=0.075 DEG
T3	0.125"	Tensile & Shear 1:1	+ Y; + X	Y=0.0007 in; X=0.0007 in
T4	0.125"	Shear Only 0:1	+ X	X=0.0017 in
T5	2.00"	Pure Tensile 1:0	+ Y	Y=0.00225 in
T6	2.00"	Tensile & Shear 1:-1	+ Y; - X	Y=0.0018 in; X= -0.0018 in
T7	2.00"	Tensile & Shear 1:2	+ Y; + X	Y=0.00125 in; X=0.0025 in
T8	2.00"	Shear Only 0:1	+ X	X=0.00425 in

Table 2 continues the original test plan's displacement vectors and notch geometries while increasing the vectors' magnitude. This allows the coupons to experience high enough loads to undergo failure while preserving the original FEA simulation's deformation direction. Each test direction was individually scaled to ensure that the new magnitude is sufficient to invoke failure in the coupon. To account for some slipping of the samples when in the grips of the machines, the distances as outlined in Table 2 instruct displacements well beyond what is required to invoke failure within the coupons. The rotational aspect of T2 was left unchanged to allow for the coupon to experience the same angle as the simulation. Following the revisions to the testing plan provided, completion of the newly listed tests began through the application of the IPL, DIC, and Instron.

In-Plane Loader

The IPL is a multiaxial in-plane loader that consists of three hydraulic actuators that can destructively pull samples in combinations of x , y , and z directions. The z direction and displacements referred to in this study represent a rotational movement about the z axis set

Table 2: Revised testing plan that maintains the original displacement vectors while increasing the magnitudes appropriate for the IPL, Instron, and DIC’s capabilities.

Test	Notch Size	Description	Direction	Magnitude	Scaling
T1	0.125"	Pure Tensile 1:0	+ Y	Y=0.50 in	x666.6
T2	0.125"	Tensile & Rotation	+ Y; + Z	Y=0.50 in; Z=0.075 DEG	x1000
T3	0.125"	Tensile & Shear 1:1	+ Y; + X	Y=0.35 in; X=0.35 in	x500
T4	0.125"	Shear Only 0:1	+ X	X=0.80 in	x470
T5	2.00"	Pure Tensile 1:0	+ Y	Y=0.35 in	x155.5
T6	2.00"	Tensile & Shear 1:-1	+ Y; - X	Y=0.50 in; X= -0.50 in	x277
T7	2.00"	Tensile & Shear 1:2	+ Y; + X	Y=0.40 in; X=0.80 in	x320
T8	2.00"	Shear Only 0:1	+ X	X=0.80 in	x188

by the existing x and y coordinate definitions. Instructions for the machine’s movements are given through instructed displacement distances in each direction, as well as maximum acceleration and velocity the IPL applies during movement. The x and y displacements are given in inches, and the rotational z displacement is given in degrees. The use of the IPL follows the work performed by previous students at Montana State University. The previous work includes creating and revising the IPL [2, 3, 14, 26–28]. The conditions as outlined per the revised testing list in Table 2 would be replicated using the inputs of the IPL in Figure 4.

IPL Assembly

The layout and structuring of the upper and lower IPL frame are shown in Figure 5. The lower frame is fixed in place and the upper frame is moved relative to the lower frame. Instructed displacements of the upper frame are controlled by three electro-mechanical actuators in between the two frames. All digital interactions with the IPL, as well as the programming of the IPL’s behavior, were done through a computer system equipped with a digital program in LabVIEW. Once given a set of instructions, the IPL uses the live updating extension readings of the 3 hydraulic actuators to accurately displace the upper frame according to the instructions.

Force readings across a test period are as important as the knowledge of displacement.



Figure 4: The IPL used to pull coupons multiaxially based on instructed displacement inputs of x , y , and z directions.

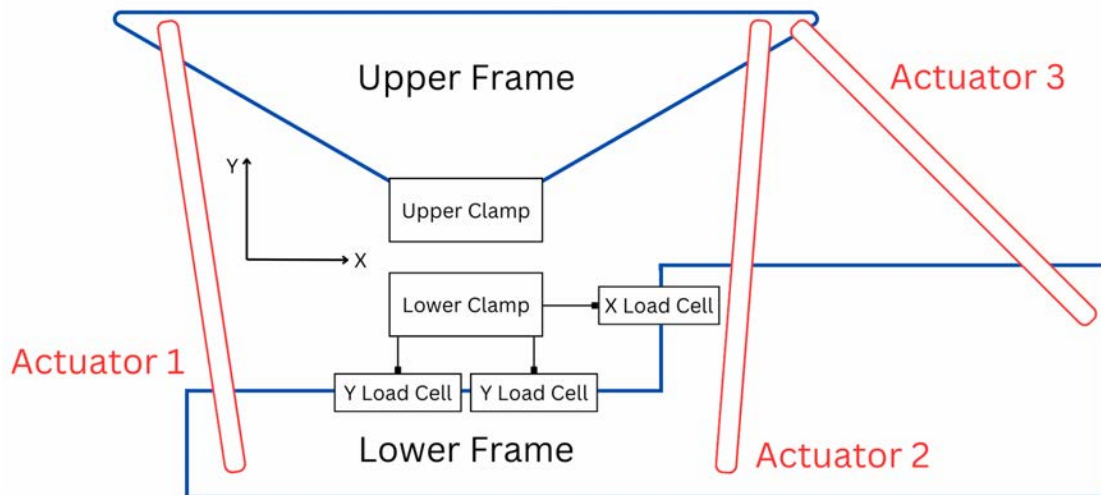


Figure 5: Diagram of the IPL showing the formatting of the three actuators, two hydraulic clamps, and three load cells.

Forces were measured through three load cells that are positioned between the lower hydraulic clamp and the lower frame itself. This allowed for the reading and measuring of forces experienced, as any force experienced in the coupon gets transmitted through the load cells. Three load cells use combinations of x and y loading data to mathematically determine the F_x and F_y forces, and the F_{xy} moment. The F_x and F_y forces are measured in pounds of force [lbf], and the F_{xy} moments are measured in inch-pounds [lbf-in].

To subject a test sample to the same displacements as the upper frame, hydraulic clamps were fixed to each of the frames. These clamps are set to fix the ends of a coupon to either frame, where any displacements experienced by the upper frame would translate through the coupon fixed in the clamps. The clamping force was manipulated by a hydraulic hand pump, and the pressure of each clamp was then displayed on a gauge. Either clamp can be closed or opened independently of one another, allowing for the increasing or decreasing of one frame's clamping strength at a time. The gauges were monitored to not exceed 6000 psi of pressure to prevent excess clamping of a sample's ends.

Both clamps additionally have a set of two transversely sliding plates that sit on either side of the coupon when placed in the clamps (shown in Figure 6). These are critical in preventing the coupon from sliding sideways in the clamps when subjected to a load or displacement. The plates were manually aligned to rest against either edge of a coupon before being tightened into place via bolts for every test.

IPL Setup

To apply accurate displacement instructions through the IPL during testing, software calibrations to virtually establish the current actuator positions must be applied. This was done through manual measurement and subsequent electronic voltage calibration. Calibration of the IPL consisted of manually measuring the lengths of all three hydraulic actuators across their points of connection to both IPL frames. These measurements were

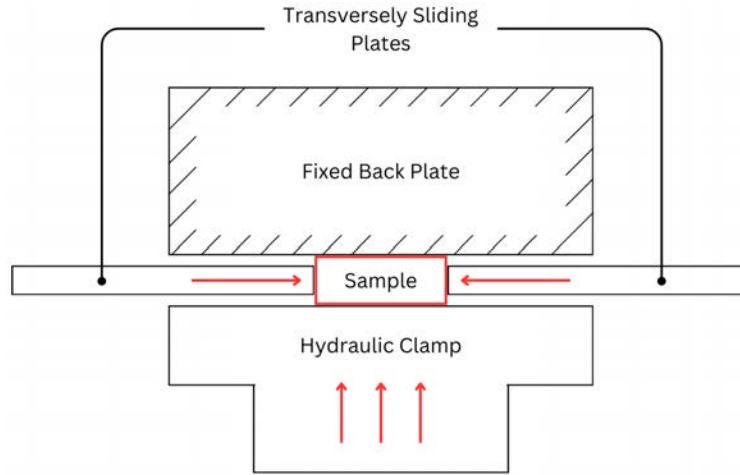


Figure 6: A top-down view of the IPL clamp structure made up of the hydraulic clamp, back plate, two transversely sliding plates, test sample, and all pieces' applied force to a sample within the clamp.

input into LabVIEW to allow the IPL to recognize the current extension lengths of all three actuators. To allow the extensions of the actuators to scale accurately, their three respective Linear Variable Digital Transformers (LVDT) voltages were referenced. The combination of actuator extension length and LVDT voltages prompt LabVIEW to check the standard deviation of the LVDT voltages according to their respective actuator lengths. Once the standard deviation of all three voltages were below 0.02 V, calibration of the IPL was complete. Calibration of the IPL was carried out after every power cycle of the machine.

To allow for the proper sampling of displacement and force data during tests, testing speeds and accelerations of the IPL's displacement instructions were slowed down. The default speeds are set to 5 in/s of maximum speed and 1 in/s² of maximum acceleration. This led to the out-of-sync sampling of force and displacement data during a test. To allow sampling to remain in sync, the maximum speed was lowered to 1 in/s, and the maximum acceleration remained at 1 in/s². This modified speed was used across the entirety of testing.

Digital Image Correlation

The GOM Aramis Adjustable Base 2.3M DIC is a dual camera and computer system designed to precisely track the displacement of black-painted dots on the surface of a part undergoing structural deformation. Since the paint is bonded to the surface of interest, the paint visible to the DIC cameras will deform exactly as the part does. This allows the change of position of the painted dots to be interpreted as the change of position of the parts' surface. Due to this, parts experiencing deformation were visually evaluated by the DIC, and calculations of strain across the parts' surface was performed by the DIC once calibrated. The work around the DIC follows the work performed by previous students at Montana State University [2, 14, 22, 30].

DIC Setup

Calibration across the working distances must be performed prior to testing to ensure accurate data collection. The GOM / CP 20 / MV 55x44 mm calibration block shown in Figure 7 was used to calibrate the sensor for every test performed.

Calibration of the DIC was carried out at the start of a testing period and was preserved throughout the following week. If the positions of the cameras were adjusted or changed in any way, recalibration of the sensors was immediately carried out to ensure the integrity of the results remained. Calibration at the start of every week was still performed regardless of if a calibration was carried out towards the end of the previous week due to the possibility of positional disturbance.

The working distances from the sample to the sensor were limited due to the DIC's tripod colliding with the bases of both the IPL and Instron. Working distances for the testing procedure ranged from 19 to 24 inches from the front face of the testing sample depending on whether the IPL or Instron was used. To properly record strain data from

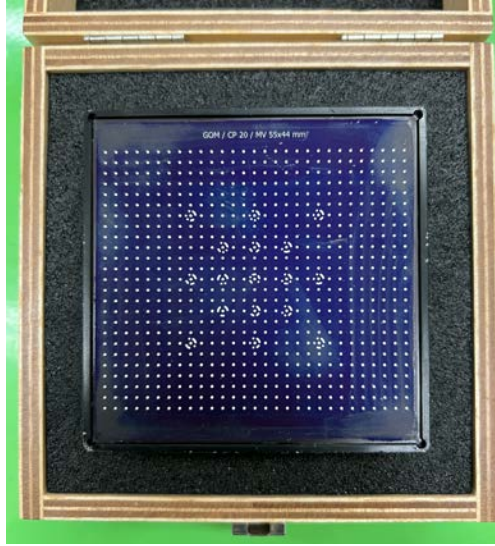


Figure 7: The GOM / CP 20 / MV 55x44 mm high-precision calibration block used to calibrate the camera system to allow the software to accurately recognize the scale of displacements recorded during testing.

this distance, the DIC's cameras were equipped with 75 mm lenses. This permitted proper viewing and framing of a test samples' painted surface, where strain data could be properly recorded across the measuring distance.

Instron

To test samples exclusively in the y direction that were too strong for the IPL's capabilities, the Instron 8562 servo-electric frame was used in tangent with the Instron 8500 electronics interface. This machine was used only after a test would fail to complete within the IPL and if the test called for exclusive y displacement.



Figure 8: Instron 8562 system used to displace coupons in exclusively the y direction if the IPL could not invoke failure within the same test.

EXPERIMENTAL TESTING

Testing of the composite samples according to the revised testing list was performed after the verification of the testing methodology. Verification consisted of testing copper samples and comparing the resulting experimental values with the materials' published values. Following the validation process, fiberglass coupons from three unique layups were manufactured for testing, where the data would be extracted and recorded through the IPL, DIC, and Instron according to the revised testing list. These tests were performed to gather stress, force, and displacement data across multiple instances for each testing direction.

Verification of Testing Methodology

Prior to the completion of the revised testing list, verification of the testing methodology was performed. This was done to confirm the resulting numbers from the applied testing methodology were accurate prior to the recording and publishing of data from subsequent fiberglass tests. To accomplish this, copper 110 coupons were pulled in tension by the IPL and recorded by the DIC to gather stress and strain data from the material. This data was then plotted to produce a stress-strain curve. Analysis of this curve permitted the extraction of resulting material properties which were then compared to the published values. Successful validation of the copper tests established the validity of not only the testing methodology, but the results from the IPL and DIC.

Copper 110 was chosen as the validation material due to copper's well documented and referable material properties, as well as an achievable yield tensile strength of 10 ksi with the IPL [13, 21]. Several coupons were machined from a 0.187 inch thick copper sheet with the purpose of tensile testing. These coupons were dimensioned to be 5.5 by 1 inches, as seen in Figure 9.

The form of the coupons permitted reliable measuring of the cross-sectional area at the



Figure 9: Example copper 110 coupons machined to be tested in tension for testing verification.

notch. This is paramount in calculating stresses experienced in a tensile test, of which is required in a stress-strain curve. Stress data was calculated by dividing the vertical force F_y by the measured cross-sectional area of the coupon's notch. Mitutoyo digital calipers were used to measure the length and width of the copper coupons' cross-section for area calculation. Each copper coupon had its cross-section individually measured and recorded for testing to ensure each coupon was accurately gauged independently.

To measure strain data, the notch of the coupon was painted white with a black-speckled paint pattern that can be recognized by the DIC. Application of paint was carried out over a multi-day process to ensure that each coat had completely dried prior to the application of another.

Coupons first had their ends covered as to prevent any paint from getting applied to them. A smooth, uniform white paint layer was first applied over the notch via spray paint. Afterwards, the coupons were left to dry overnight. Following the white coat application, quick, rapid bursts of the black spray paint were then applied over the notches to apply a



Figure 10: Fiberglass double notch sample painted with the ideal black and white finish for DIC testing purposes.

sporadic, nonuniform pattern of black dots against a white background (Figure 10). The black and white paint consisted of a flat finish to eliminate the possibility of light reflection on the painted surface. Copper strain data was calculated through the DIC using a virtual extensometer that spanned the vertical length of the painted notch in Aramis. This allowed for the accurate recording of vertical strain data throughout a copper tensile test with the presence of a thin notch.

Following the testing of copper samples, resulting sets of stress and strain data were gathered. Each coupon's data set was plotted in Excel as a stress-strain diagram, where the slope of the linear elastic region corresponds to the materials' elastic modulus, and the stress value in which the curve becomes nonlinear corresponds to the yield tensile strength (see Figure 11).

The published material properties for annealed copper 110 are an elastic modulus of 17,000 ksi, and a yield tensile strength of 10 ksi [13, 21]. Analysis of the experimental data showed the extracted values of the elastic modulus ranged from 16,300 to 21,300 ksi, averaging 18,835 ksi across the four successful tests. The yield tensile strength of the tests

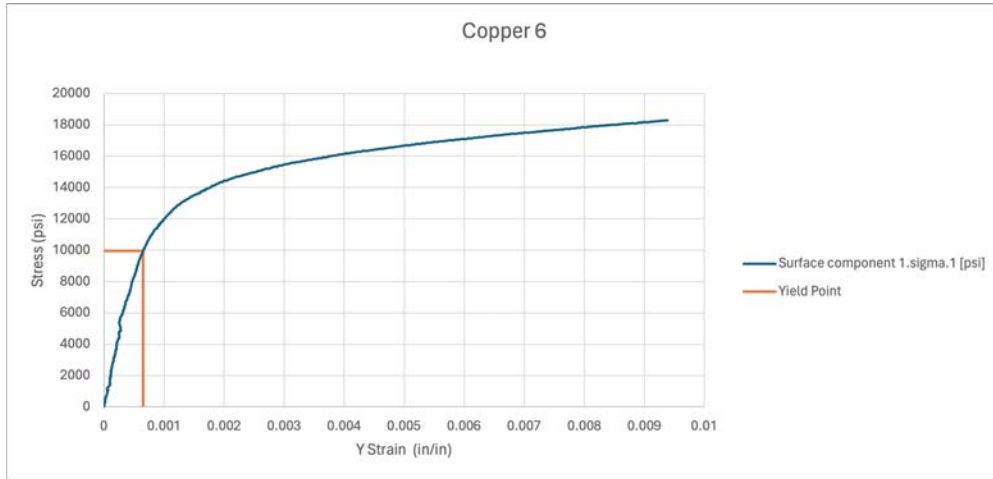


Figure 11: Stress-strain curve from copper 110 tensile test showing the corresponding stress and strain values at the tensile yield point.

were 9.9, 8.1, 7.2, and 13.6 ksi, averaging a value of 9.7 ksi. Both the elastic modulus and yield tensile strength results were very close to the published values of 17,000 ksi and 10 ksi, respectively. Variation in the results can be attributed to the imperfect vertical displacement performed by the IPL and the unideal surface paint quality. Following the successful validation of the testing methodology and resulting numbers from the IPL and DIC, completion of the revised composites testing list began.

Testing of Fiberglass Samples

Coupons were made from uniaxial, biaxial, and triaxial fiberglass layups in batches that spanned across multiple days. Coupons made from each of the layups and were divided into the two separate notch geometries according to the testing list. The testing of samples was iterated over multiple times per testing direction to gather repeated data points. Only once results from a testing direction consisted of at least three strain data points that were generally close together in 3D space would that testing direction for that layup be considered complete.

Manufacturing of Composite Samples

To successfully test three layups across eight directions, many coupons were required. Inventory consisted of excess uniaxial and biaxial fiberglass coupons, both consisting of four plies and a Westlake 035c/0366 resin system [6]. The uniaxial samples are a $[0^\circ]_4$ layup, and the biaxial samples are a $[\pm 45^\circ]_4$ layup. To keep consistency across all testing samples, the remaining triaxial layup was manufactured with the same resin system as the other laminates, and was made up of four plies in the form of $[\pm 45^\circ/0^\circ/\pm 45^\circ/0^\circ]_s$. The uniaxial layup was made with a Saertex stitched unidirectional fabric [9], the biaxial layup was made with a Saertex stitched biaxial fabric [8], and the triaxial layup was made with a Saertex stitched triaxial fabric [10].

All plates were manufactured through a vacuum infusion process. The resin system was cured on a mold plate at 120° Fahrenheit [F] for 24 hours. After this, the plate was moved to an oven at 158° F for approximately six hours to finish curing. From the plates, rectangular coupons were cut to the same 5.5 by 1 inch dimensions as the copper coupons. The rectangular coupons of all three layups are then notched to shape using a pin router. Molds of both notch geometries were made for the pin to trace when cutting coupons. The resulting notch edges were then sanded to remove stray fibers leftover from the pin routing process. Coupons were numbered with a three-digit numbering scheme following the notching process to keep track of each coupon's properties and measurements. The smallest cross-section at the notch for every sample was measured with digital calipers and recorded. Following the measurement of the cross-sectional area, both faces of the coupon's ends were tabbed using 0.062 inch thick G10 fiberglass. The notches of the coupons were painted the same way as the copper samples were painted in Figure 10.

Fiberglass Testing

Testing began following the manufacturing of testing samples for all three layups. Tests were carried out through the IPL with the DIC recording each test. Each layup was tested to completion prior to the testing of another. For each layup, one testing direction was tested to completion before the testing of another direction began. Each test performed was deemed completed following a successful data analysis process through the DIC. Data from the DIC must display complete footage of a sample undergoing the full deformation process prior to breaking for a certain test to be considered successful. For a testing direction, three to five instances of a successful test were required for that testing direction to be considered complete.

Impeded Testing Completion and Revisions

All tests were initially performed with the DIC and IPL. Due to the strength of some of the double notched fiberglass coupons and the limited grip strength of the IPL, some tests were initially incapable of being completed. This prompted a redesign of a double notched coupon, as well as a need to use the higher load capability of the Instron. A redesign of the double notched coupon was necessary to invoke failure with the present strength of the materials used. The diameter of the notch cuts was left unchanged, but the minimum width of the notch was reduced from 0.50 to 0.25 inches wide, as seen in Figure 12.

The redesigned notch allowed for a smaller required force to invoke failure within the coupon when testing. The revised coupon shape was used for the T5, T6, and T7 testing directions for the uniaxial and triaxial layup samples (see Table 2), but not all instances of the T5, T6, and T7 direction for the uniaxial and triaxial layups entirely required the revised notch to reach failure. As a result, the successful tests for those directions were split across the original and revised double notch. Since the Instron was capable of replicating the T5 testing direction conditions, it was used to complete the T5 testing direction for both the

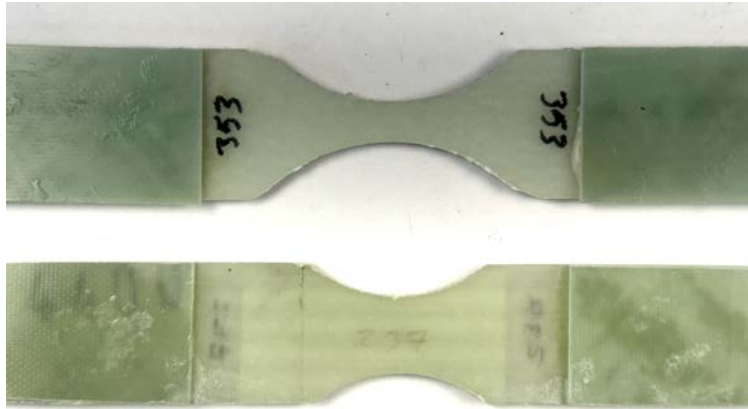


Figure 12: Revised (top) and original (bottom) double notch coupon geometry used for testing.

uniaxial and triaxial samples. The IPL was required to test the T6 and T7 testing directions due to the required multiaxial conditions. Through the IPL, the uniaxial completion of the T7 direction was not possible despite the smaller notch. This resulted in the data for the T7 testing direction for the uniaxial layup remaining incomplete. Following the completion of testing, analysis of the resulting data began.

ANALYSIS PROCESS

The data extraction process began with the Aramis software. Resulting numbers from Aramis were then plotted in Excel to identify a point of failure during a test. Once a point of failure was determined, all key values from that test during that point in time were extracted and plotted in MATLAB as a scatter plot to view results from all testing directions per layup.

Aramis Process

During testing, once the coupons were first inserted into the grips of either the IPL or Instron, and a reference picture was taken. In the reference picture, a virtual surface component was projected onto the painted surface of the sample, and the quality of the surface component was evaluated prior to testing. (see Figure 13). The virtual surface component was used in all strain calculations for every test performed. The quality of the surface component was directly related to the calibration performed on the DIC and the paint application on the surface of the coupon. Coupons that displayed poor surface quality were not tested to preserve the integrity of recorded data. Once a surface component was successfully validated as good quality on a sample ready to test, recording with the DIC began and the test was conducted.

Following the performance of a test, x , y , and z coordinate directions were defined on the surface component around the exact orientation of the coupon (see Figure 14). This allowed for a consistently defined coordinate system across all samples tested. The y direction was aligned along the length of the coupon, and the z direction to face towards the DIC for every test performed.

Coordinate definition was performed on the surface component projected onto the coupon in Aramis. All coordinate alignments were performed using the 3-2-1 method. This method consisted of placing three z reference points across the surface, then two x

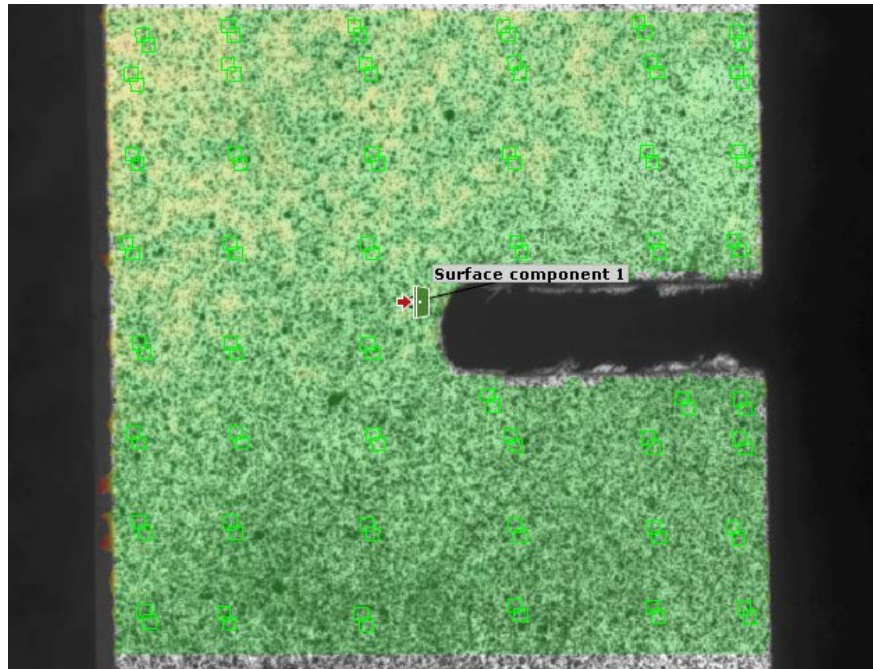


Figure 13: Surface component showing the applied facet points virtually overlaid onto a painted single notch fiberglass sample.



Figure 14: Coordinate plane defined on the surface component of a coupon in Aramis.

reference points along the spine of the coupon, then finally one y reference point to define the orientation of the y axis. The three z reference points defined where direction in which the face of the coupon was perpendicular to, the x reference points defined the vertical angle of the coupon, and y reference point defined the relative directionality of all three axes. The defining of a coordinate system was paramount to the accuracy and application of the ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} directional strains experienced in the coupon across a test.

Data extraction in Aramis consisted of virtually probing the ϕ_M strain value at the apparent ϕ_M concentration on the coupon. The extraction of the ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strain values were then done at the same location of the probed ϕ_M value (see Figure 15). This was done to allow the extraction of all directional strain once a point of failure was determined. The directional strains at failure indicate the combinations of strains that lead to failure of a coupon. Several plots of these combinations of strains across several varying invoked failure directions outline a strain failure curve that can be used to better predict failure among composites.

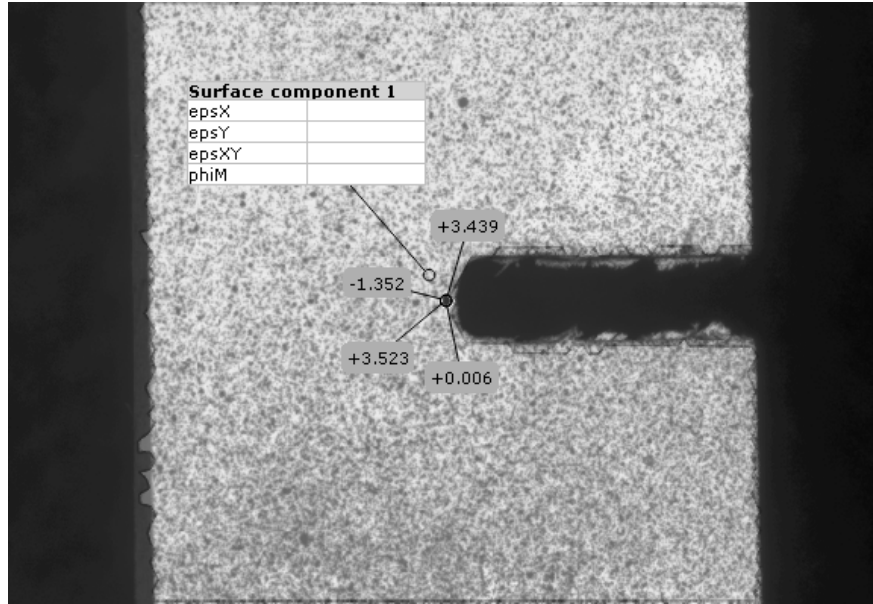


Figure 15: Surface component showing the location of the probed ϕ_M , ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strain values on the same location on a coupon.

Following the strain data extraction, the F_x , F_y , and F_{xy} loading values were calculated from the analog input voltages. Force voltages were recorded throughout the entirety of a test (see Figure 16), and the directional force data for all tests were manually zeroed to correct any persisting force voltages from previous tests performed.

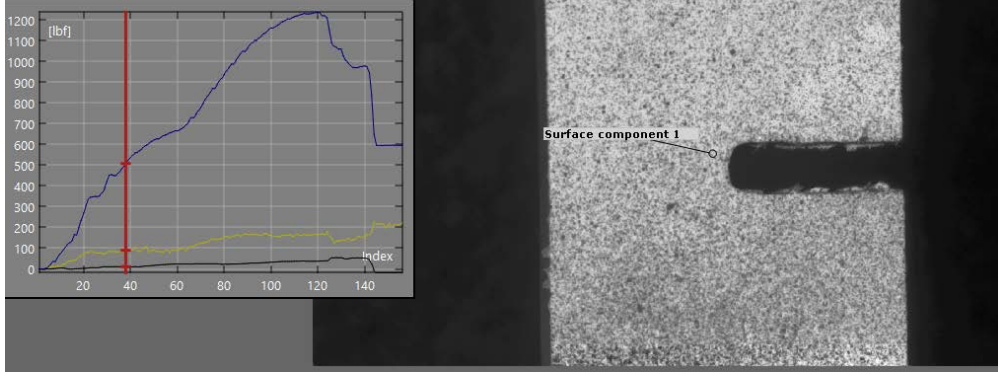


Figure 16: Aramis showing the plotted F_x , F_y , and F_{xy} loads over time from a recorded test performed.

Throughout a test, the load cells on the IPL and Instron outputted voltages that had to be translated back into loads. The IPL used conversion factors of 500 lbf / V for the F_x and F_y forces, and a conversion factor of 8000 lbf-in / V was used for the F_{xy} moment. For the Instron tests, forces were exclusive to the y direction, and a conversion factor of 2248 lbf / V was used to translate the recorded voltage into units of force. One limitation from Aramis was the lack of displaying a load through units of moment. As such, the moment load from Aramis, and subsequently in the Aramis reports and Excel analyses, is incorrectly displayed as [lbf] instead of the correct units of [lbf-in].

Since no two coupon results are identical, each test performed needed to be inspected and virtually probed independently of one another. To expedite the analysis process around this, scripts were used to calculate all the resulting F_x , F_y , and F_{xy} loads from the received voltages and the ϕ_M , ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strain values experienced across the entire coupon during the test (see Appendix D). This allowed for the exact same types of calculations to be performed for every test recorded. Following the successful recording of all seven key

values across an entire test, the data for that test was exported as a comma-separated values (CSV) file to plot in Excel for further data analysis.

Excel Process

Excel analysis consisted of plotting each of the F_x , F_y , and F_{xy} loading data against the probed ϕ_M strain value of a test. The resulting curves were independently analyzed for a point when they first display nonlinearity (see Figure 17).

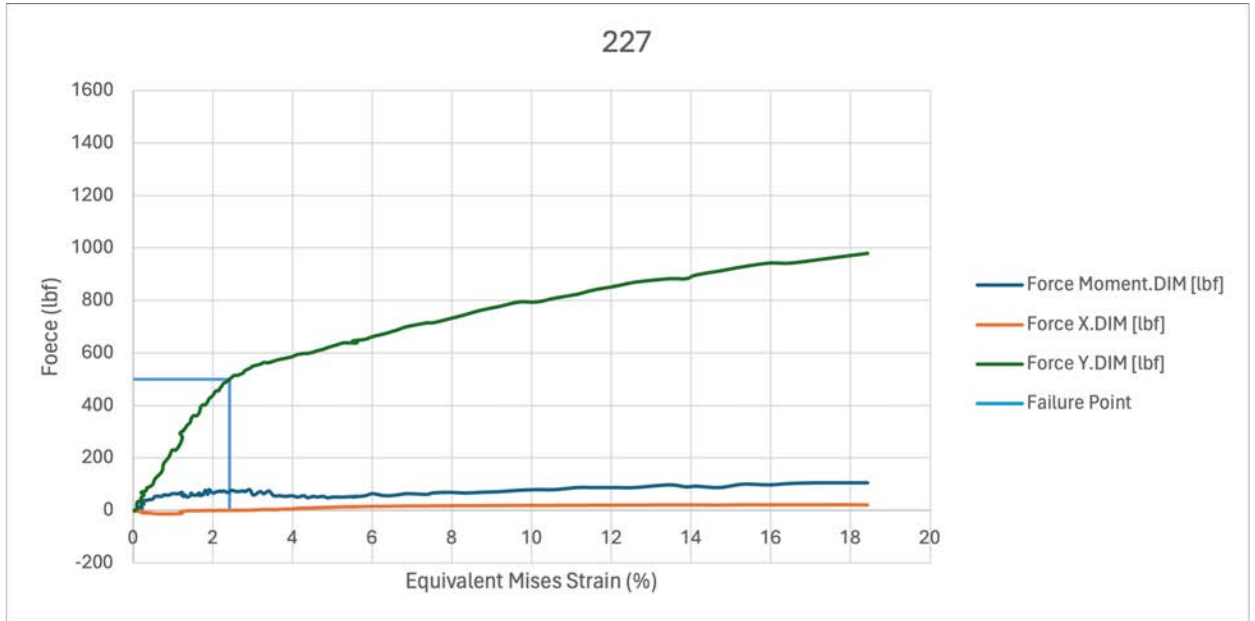


Figure 17: Example Excel analysis of the biaxial sample 227 showing the point of nonlinearity of the F_y force against the Equivalent Mises strain, ϕ_M .

Nonlinearity of the curves was chosen as failure identification since it represents FPF in the coupon. Once the point in time of nonlinearity was determined, the ϕ_M , ϵ_{xx} , ϵ_{yy} , ϵ_{xy} , F_x , F_y , and F_{xy} values are all recorded at that point in time during the test. This process was repeated for every test performed, and all data values are recorded to be referenced by MATLAB code.

MATLAB Process

The application of MATLAB allowed for the importing and plotting of all Excel data previously gathered from testing. MATLAB code was made to import Excel files, read the data from the recorded points of nonlinearity for each test, and plot the ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strain values as a point in 3D space. This allowed for the examination of patterns in the varying combinations of ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strain values that occur during nonlinearity. Additionally, the MATLAB code also plotted the F_x , F_y , and F_{xy} loads in a 3D scatterplot to help view the combinations of loads that led to nonlinearity in the samples. The MATLAB code used is shown in Appendix E.

Error Sources

Several error sources were present in several parts of the testing procedure. These errors were either unavoidable or minimized throughout the testing process.

IPL Displacement Errors

The IPL would exhibit displacements in both the x and y directions regardless of if instructed to displace in exclusively one direction or the other. The magnitude of the unintentional displacements was small, but present. As a result, the displacement vectors as outlined in Table 2 were unable to be remade exactly. Despite this, the resulting data was still sound due to the strain conditions varying from a wide range of invoked failure conditions.

IPL Coupon Slippage

Coupons held in the grips of the IPL did not always remain static in them. The grips of the IPL occasionally allowed the coupons to slip when the coupons were subject to a vertical displacement. Additionally, the transverse sliding plates within the IPL's grips would also

slip sideways when a coupon was subject to a shear displacement. Both behaviors allowed for imperfect conditions to be applied a coupon when subject to explicit instructions. To work around this, the displacement magnitudes in the revised testing list (seen in Table 2) were scaled far beyond the expected failure point.

Paint Quality

The painting quality of samples for use of the DIC had a direct correlation with data quality. The ideal paint pattern consists of several fine black dots spread over a white background with no repetition in the pattern (seen in Figure 10). Pattern quality through the DIC was directly related to the application of white and black paint to the notch of a coupon. In addition to paint quality, the edge of a sample has notably poor accuracy with strain data. In Aramis, strain is calculated through the displacements of painted black dots on the surface of a part relative to the surrounding black dots. This leads to inaccurate calculations of strains at the edges of a sample, as the edge of a sample has significantly less reference points around it to calculate strains. To work around this, strain concentrations seen at the edge of a sample were instead probed slightly away from the edge along the path of crack propagation. This was done to lose minimal accuracy in the probing process. Strain combinations at failure were still valid further from the edge as the combinations of strain that led to failure still occur along the crack even if a crack begins at an earlier instance at the edge.

Probing Error

Strain data was calculated through the DIC but probed manually on the surface of the sample for each test. Strain values within the Aramis software vary by pixel on the surface of a coupon. As a result, the variation of the probed values varied depending on what pixel was selected within Aramis. This had a small effect on the data, but data that did not include fair precision in a set of results for a given test were discarded.

FPF Identification Error

Excel data, much like the probed Aramis strain values, were manually inspected for nonlinearity within the resulting force-strain curves. This led to slight discrepancy between the actual point of nonlinearity, and the actual point of nonlinearity for tests. This was minimized by inspecting the precision of all instances of all testing directions. A lack of precision among the repeated instances of the same test led to reprobing in Aramis and the reevaluation of a nonlinearity point in Excel. This process was repeated for all tests when needed until at least three precise strain data coordinate points were present for all testing directions.

RESULTS AND DISCUSSION

Finalization of the scatter plots and data tables allow for the viewing and understanding of the relationship between the different combinations of directional strain a given sample undergoes at the time of failure. Recorded forces for all tests at the instance of nonlinearity provide a foundation for future recreations of the tests in FEA. Remodeling of the laboratory experiments using the actual experienced forces for each test provide the necessary means for the calculation of actual experienced stresses for each test. All data is presented in 3D scatter plots that were oriented in three separate top-down views from each axis to view the 3D data in 2D space. All three orientations of the scatter plots allow for the viewing of all data points in x - y , y - z , and z - x space.

Uniaxial Coupon Results

The $[0^\circ]_4$ uniaxial test coupons displayed vague patterning across the eight performed test directions (see Figure 18). Of the tests performed, the T7 test direction was performed upwards of eight times, and no three resulting strain combinations were close enough together to establish the validity of their results. As such, the uniaxial T7 tests were excluded from the main data sets by having their results set to $(0, 0, 0)$ in the strain scatter plots, and excluded from the force scatter plot. Some tests displayed negative ϵ_{xx} strain results from one test direction but were of similar ϵ_{xx} magnitude to the other instances of that same test. As such, their results appear isolated from the entirety of the results, but their only difference was the sign of their ϵ_{xx} value and were included with the overall scatterplot for their similarity. A vast majority of all uniaxial tests performed resulted in positive combinations of ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strains. Of the tests performed, most resulted in positive F_x and F_y forces and negative F_{xy} moments.

The T1 through T4 directions consisted of the single 0.125 inch diameter notch

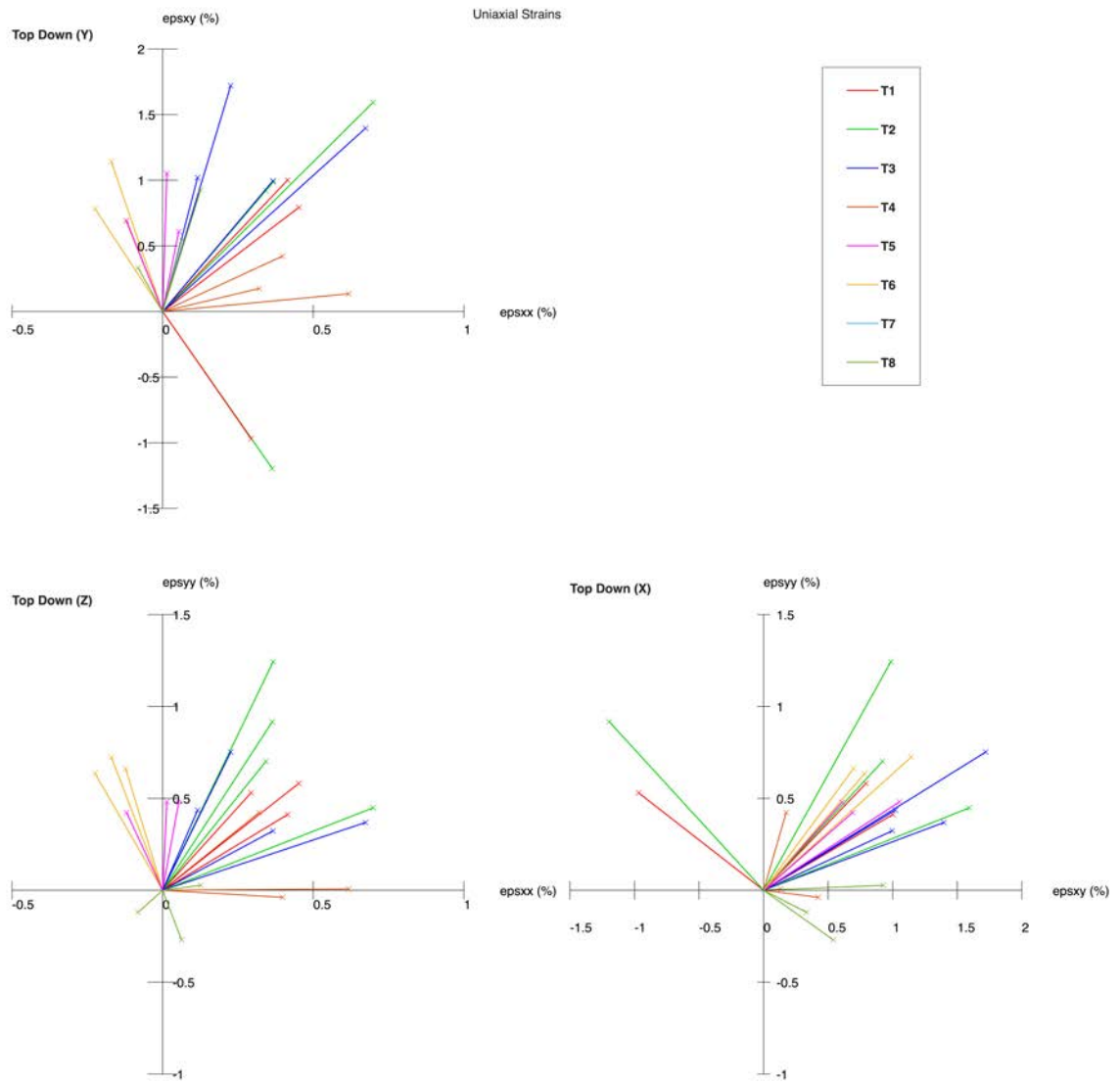


Figure 18: Uniaxial sample test results showing the strain combinations at failure across all eight test directions.

(Table 2). The T1 and T2 directions in bright red and bright green, respectively, showed similar results across all instances of those tests. All strains showed positive ϵ_{xx} and ϵ_{yy} values, while all but one showed positive ϵ_{xy} values for both test directions. The one instance of negative ϵ_{xx} differs from the other values only in signage, as the magnitude of all ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} values are very similar. The change in testing direction from T1 to T2 caused higher magnitudes of ϵ_{yy} strain beyond error with the addition of a rotational aspect of 0.075 degrees (Table 2). The T3 and T4 directions in dark blue and dark orange, respectively, both displayed positive ϵ_{xx} and ϵ_{xy} values. The T3 tests additionally all showed positive ϵ_{yy} values while the T4 tests showed values that were either close to zero, or positive ϵ_{yy} strain. The T3 and T4 test directions both independently displayed similar magnitudes among their results. The T5 through T8 directions consisted of both the original and revised double notch coupon geometry (seen in Figure 12). Both the T5 and T6 directions in bright pink and dark yellow, respectively, displayed great precision among their results. The T5 direction showed positive ϵ_{yy} and ϵ_{xy} strains with ϵ_{xx} values close to zero. The T6 direction results all displayed negative ϵ_{xx} values and positive ϵ_{yy} and ϵ_{xy} values. The T8 direction in dark green displayed good precision in their results. All instances showed positive ϵ_{xy} values but hovered around positive and negative ϵ_{xx} and ϵ_{yy} values. The overall magnitude for the strains were the smallest, but no other test direction displayed multiple instances of negative ϵ_{yy} strain. The raw data numbers for the uniaxial samples are seen in Table 3.

With each test performed, the directional forces F_x , F_y , and F_{xy} were also recorded at time of failure for each test. These forces, like the strain values, were also plotted in a 3D scatter plot to view and understand the combinations of forces the invoked FPF within a coupon. The uniaxial force plots are shown in Figure 19.

The combinations of forces that led to failure were far more precise than the strain plots. The T1 and T2 directions in bright red and bright green, respectively, displayed great precision among their results. The T1 direction displayed positive F_x and F_y forces, and

Table 3: Uniaxial sample results showing the detailed combinations of loads and strains occurring at failure. Each coupon's associated notch dimensions are found in Appendix A.

Test	Sample	Fxy [in-lbf]	Fx [lbf]	Fy [lbf]	ϵ_{xx} [%]	ϵ_{xy} [%]	ϵ_{yy} [%]
T1	119	61.165	12.772	750.359	0.2935	-0.9684	0.5300
	118	-25.703	201.798	598.531	0.4521	0.7928	0.5813
	117	-4.79	255.448	833.696	0.4149	1.0007	0.4121
T2	116	3.228	-35.202	771.598	0.3644	-1.1966	0.9178
	111	-1.588	311.631	828.587	0.3427	0.9209	0.7014
	115	-4.949	301.422	840.721	0.3671	0.9862	1.2439
	124	-54.11	378.045	767.123	0.6984	1.5922	0.4483
T3	114	-57.307	173.697	687.478	0.1161	1.0203	0.4357
	122	-61.111	166.048	649.468	0.3662	0.9955	0.3231
	126	-77.902	199.292	699.791	0.2262	1.7207	0.7522
	124	-53.471	349.954	711.724	0.6736	1.3959	0.3687
T4	112	-147.996	56.199	104.252	0.3979	0.4219	-0.0380
	120	-128.362	143.054	38.526	0.6180	0.1350	0.0068
	129	-207.546	163.484	-69.768	0.3203	0.1751	0.4231
T5	134	-	-	1398.47	-0.1193	0.6898	0.4226
	140	-	-	1769.578	0.0142	1.0532	0.4812
	142	-	-	1337.453	0.0534	0.6078	0.4789
T6	176	-65.422	97.626	620.598	-0.1228	0.6960	0.6616
	138	34.964	-20.425	1070.141	-0.2245	0.7830	0.6358
	153	139.696	99.676	1150.794	0.0550	1.1025	0.4364
T7	-	-	-	-	-	-	-
	-	-	-	-	-	-	-
	-	-	-	-	-	-	-
T8	135	-319.091	278.449	-341.168	0.1262	0.9266	0.0269
	144	-196.689	252.893	-286.408	-0.0815	0.3322	-0.1196
	155	-270.766	201.802	-207.54	0.0629	0.5393	-0.26960

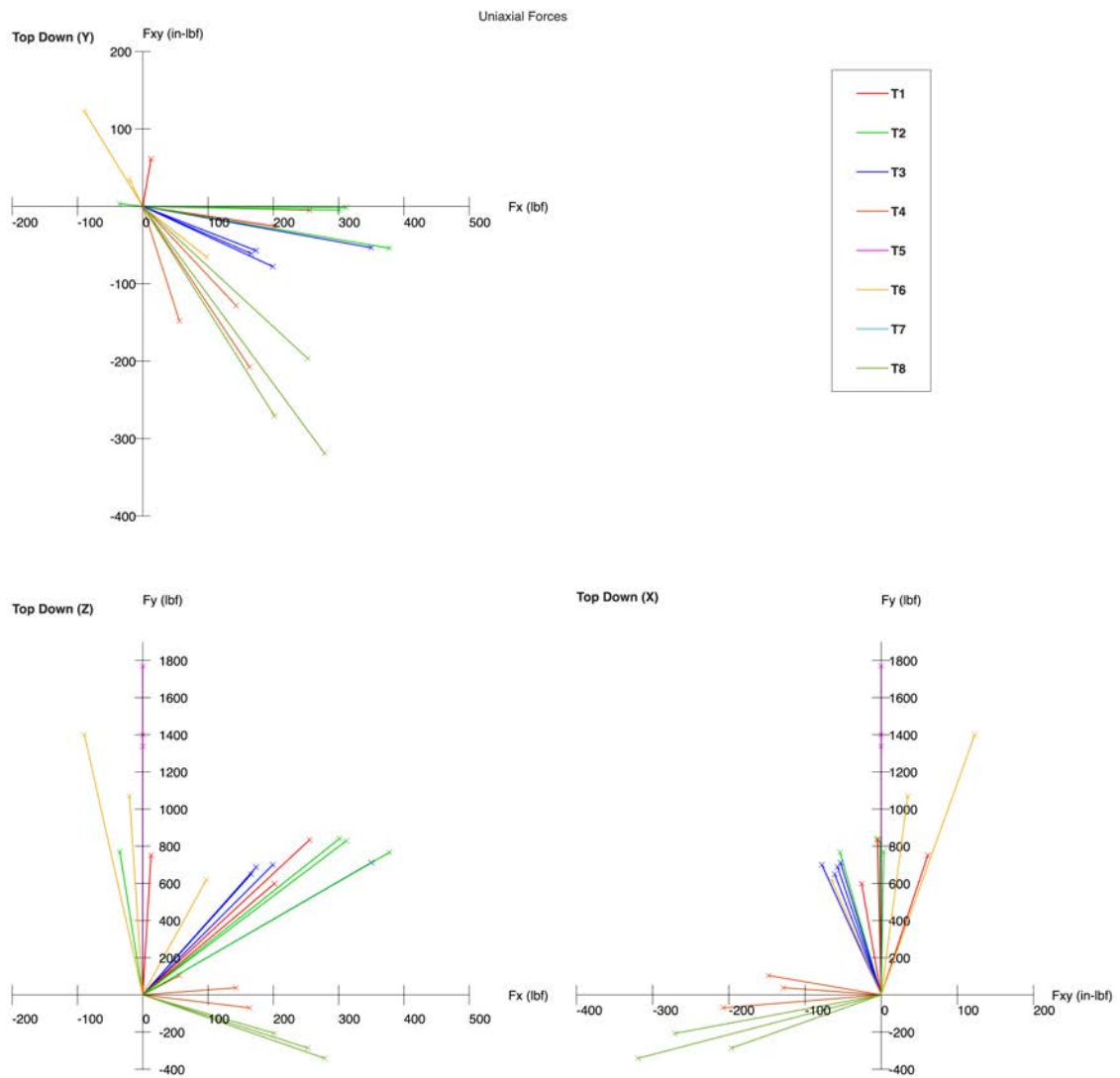


Figure 19: Uniaxial sample test results showing the combinations of directional forces at failure across all eight test directions.

mostly negative Fxy moments. One instance of a positive Fxy moment occurred for T1, and with it significantly less Fx forces were present at failure for that test. This shows an inverse relationship between the Fx force and Fxy moment required for failure in this instance. The T2 direction displayed near zero Fxy moments, all positive Fy forces, and mostly positive Fx forces. One instance of a negative Fx force occurred on the only T2 test that included a small, but positive Fxy moment. The T3 and T4 directions in dark blue and dark orange, respectively, showed similar magnitudes and good precision. The T3 direction showed exceptional precision in resulting forces, and consistently resulted in positive Fx and Fy forces, and negative Fxy moments. The T4 direction also displayed positive Fx forces and negative Fxy moments, and the Fy forces were close to zero, but not always positive. The magnitude of the Fy forces in T4 are considerably lower than any other non-exclusive shear testing directions. This pattern is most notably seen in the T4 and T8 directions of the uniaxial and triaxial tests. These tests consisted of exclusive instructed x displacements for layups consisting of a $[0^\circ]$ layer. The negative Fy forces seen in the T4 direction were a resulting reaction from an imperfect exclusively shear testing direction. Negative Fy forces would ideally never occur across testing, but their presence displays the imperfection in the IPL's behavior when subjected to explicit instructions. This imperfect behavior occurred throughout all tests and is most notably present here.

The T5 and T6 directions in bright pink and dark yellow, respectively, displayed fair precision in their results. The T5 direction was performed on the Instron, not the IPL. This caused the forces to be measured only in the y direction as Fy , and any possible loads in the x or z could not be measured. Despite this, the Instron is an incredibly more precise machine than the IPL, and the likelihood of Fx forces or Fxy moments being present under operation of the Instron is incredibly unlikely. The T6 direction consisted of exclusively positive Fy forces. Both the Fx forces and Fxy moments consisted of both positive and negative values. The instance consisting of the smallest Fy force was accompanied by the

only negative Fxy moment in this direction. This implies an inverse relationship is present between the Fy force and Fxy moment in this instance. The T8 direction in dark green displayed great precision and sign consistency throughout. All values consisted of a positive Fx force and a negative Fxy moment. All values consisted of also a present, negative Fy force. As seen in the uniaxial T4 tests, the magnitude of the Fy forces seen in the T8 direction are considerably lower than the other uniaxial tests performed. Since T8 is also an exclusively shear direction (see Table 2), no Fy forces should ideally be present, once again implying the imperfections in the IPL's directional behavior.

Uniaxial Breaking Patterns

Across all uniaxial tests performed, coupons would break and fail in repeated patterns across test directions. These patterns grant insight into the greater specifics of loads and stresses the coupon is experiencing at time of failure.

The uniaxial samples subjected to the T1, T2, T3, and T4 test directions all displayed the same failure patterns. Strain concentrations began at the notch, which led to crack propagation proceeding along the fiber direction away from the notch towards both ends of the coupon. After failure occurred in the coupons, the vertical crack propagation would continue further along the length of the coupon the longer the coupon was subject to greater and greater displacements (see Figure 20).

The uniaxial samples subject to the T5 and T6 test directions showed the same failure patterns. Due to the double notch design of the T5 through T8 test directions, less stress concentrations occurred at the midpoints of the notches. This led to vertical crack propagation beginning at the upper endpoints of the notches on four points across the coupon, where each crack propagated away from the notch continuously until the coupon was no longer subject to the displacement (see Figure 21).

The uniaxial samples subject to the T8 test direction displayed unique failure patterns

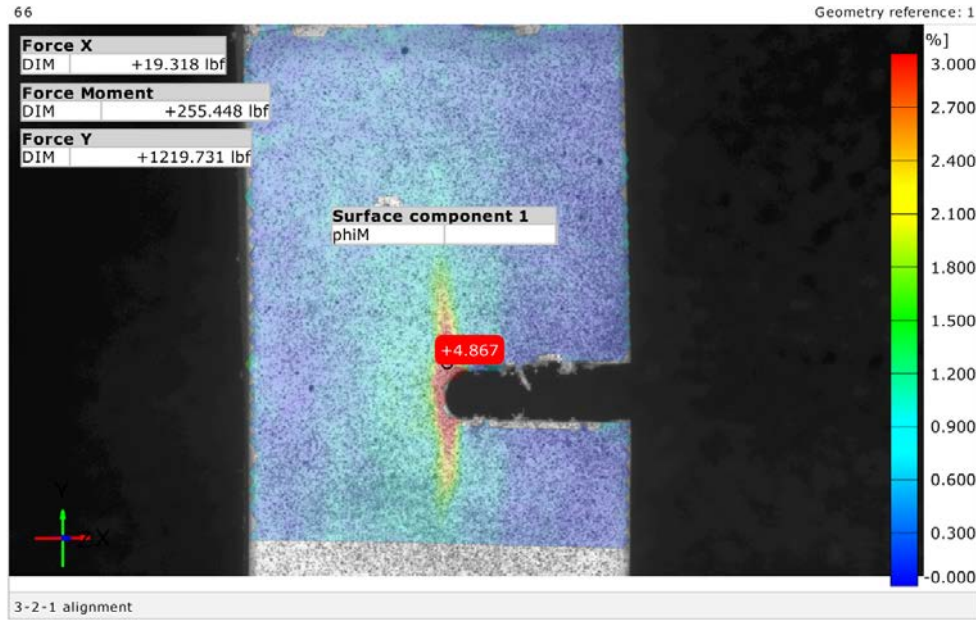


Figure 20: Uniaxial T1 test representing the T1 through T4 failure pattern as seen through the ϕ_M strain concentrations in Aramis.

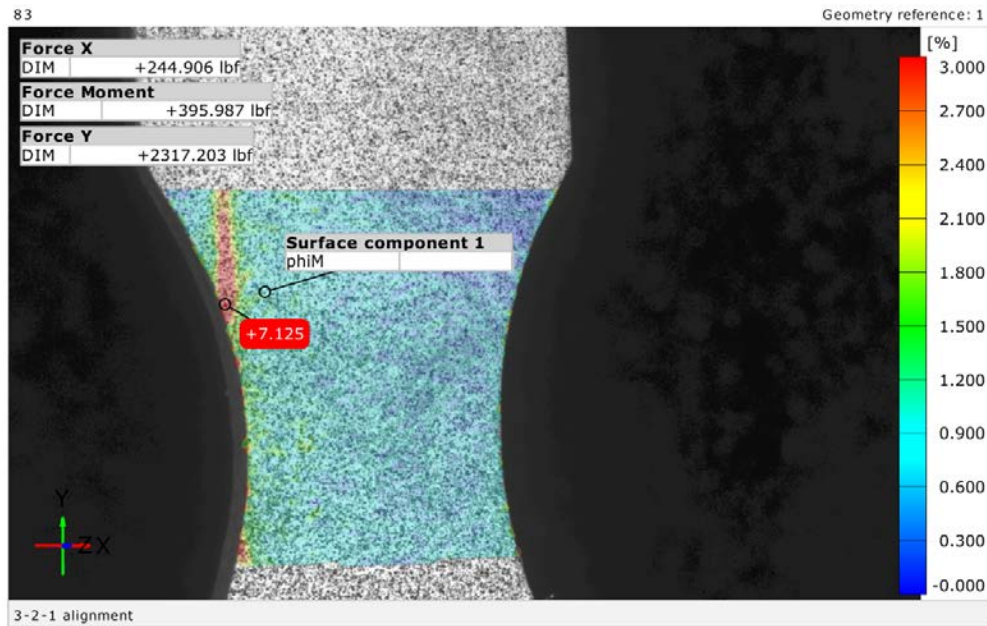


Figure 21: Uniaxial T6 test representing the T5 and T6 failure pattern as seen through the ϕ_M strain concentrations in Aramis.

in comparison to the rest of the uniaxial test directions. The entire midsection of the coupon suddenly failed perpendicularly to the length of the coupon across the entire width of the coupon at once. This was due to matrix dominated failure of the sample because of the coupon's fibers oriented perpendicular to the exclusive shear load (see Figure 22). Additional, smaller strain concentrations are seen oriented along the $[0^\circ]_4$ fiber directions, perpendicular to the experienced horizontal failure from shear displacement.



Figure 22: Uniaxial T8 failure pattern as seen through the ϕ_M strain concentrations in Aramis.

Biaxial Coupon Results

The $[\pm 45^\circ]_4$ biaxial test sample strain combinations seen in Figure 23 displayed the most precise results. This was due to failure being largely matrix dominated, causing the strain concentrations on the surface of the sample to be very distanced from the edges of the coupon. This behavior catered to the strengths of the DIC and its calculation of strain based on the distancing of relative surrounding points on a surface component. Almost all

test samples resulted in negative ϵ_{xx} , positive ϵ_{yy} and positive ϵ_{xy} strain with few exceptions. Resulting forces from the biaxial tests mostly resulted in positive F_x and F_y forces, and negative F_{xy} moments. The biaxial tests also resulted in the greatest magnitude of ϵ_{yy} strain of the three layups.

The T1 through T4 testing directions for the biaxial layup all consisted of the single 0.125 inch diameter notch. The T1 and T2 directions in bright red and bright green, respectively, both displayed fair strain precision. The T1 and T2 direction results both showed negative ϵ_{xx} and positive ϵ_{yy} and ϵ_{xy} strain. One test from T1 displayed an ϵ_{xy} value far greater than the others. This test was also accompanied by the smallest ϵ_{xx} value, implying an inverse relationship between ϵ_{xy} and ϵ_{xx} . The T3 and T4 directions in dark blue and dark orange, respectively, displayed fair precision. The strain results for both T3 and T4 showed consistent, positive ϵ_{yy} values. All ϵ_{xx} values were negative for these two directions, with one T4 ϵ_{xx} value consisting of considerably less magnitude than the other tests. This test simultaneously resulted in the highest ϵ_{xy} value, implying an inverse relationship between ϵ_{xx} and ϵ_{xy} . For the T5 through T8 testing directions of the biaxial layup, all coupons consisted of the original 2.00 inch diameter notch. The T5 and T6 directions in bright pink and dark yellow, respectively, both showed great strain precision. For both T5 and T6, the ϵ_{xx} values were negative, the ϵ_{yy} values were positive, and the ϵ_{xy} values hovered close to zero. The T7 and T8 directions in light blue and dark green, respectively, showed good precision. For T7, the ϵ_{yy} values were positive, the ϵ_{xx} values were negative, and the ϵ_{xy} values hovered close to zero. For T8, the ϵ_{yy} values were negative, and the ϵ_{xx} and ϵ_{xy} values were positive. The raw data numbers for the biaxial samples are seen in Table 4.

The directional forces F_x , F_y , and F_{xy} recorded at time of failure for each test displayed far greater overall precision than the strains. Shown in Figure 24, consistency among results in a testing direction was far greater than the uniaxial force results. The T1 force results showed excellent precision. T1 consisted of positive F_x and F_y forces, and near zero F_{xy}

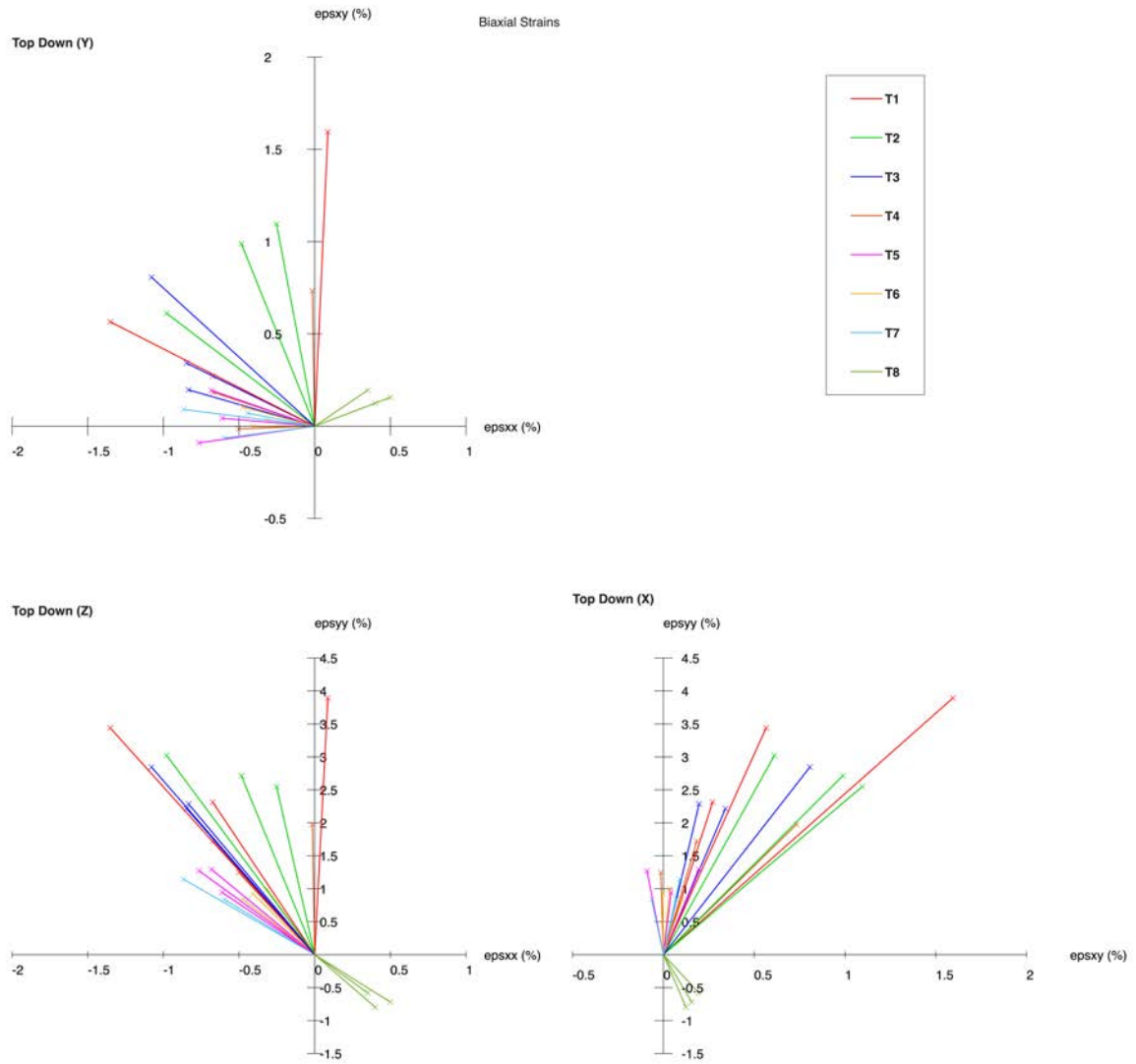


Figure 23: Biaxial sample test results showing the strain combinations at failure across all eight test direction.

Table 4: Biaxial sample results at failure showing the detailed combinations of loads and strains occurring at failure. Each coupon's associated notch dimensions are found in Appendix A.

Test	Sample	F_{xy} [in-lbf]	F_x [lbf]	F_y [lbf]	ϵ_{xx} [%]	ϵ_{xy} [%]	ϵ_{yy} [%]
T1	216	2.472	79.195	442.400	0.0872	1.5941	3.8916
	224	10.700	89.453	507.689	-1.3515	0.5657	3.4388
	227	-0.163	71.523	499.410	-0.6735	0.2709	2.3134
T2	215	2.555	-48.517	477.844	-0.4843	0.9881	2.7149
	222	-12.447	-2.563	471.696	-0.9786	0.6114	3.0229
	226	7.832	-22.972	408.873	-0.2519	1.0954	2.5490
T3	209	-35.903	120.059	373.105	-0.8338	0.1969	2.2864
	213	-25.063	99.628	394.342	-0.8469	0.3416	2.2139
	219	-36.071	51.087	337.044	-1.0782	0.8068	2.8445
T4	202	-154.401	204.349	323.137	-0.6709	0.1840	1.7221
	203	-105.213	183.924	270.929	-0.5031	-0.0142	1.2473
	225	-184.716	160.943	214.419	-0.0154	0.7334	1.9757
T5	244	-14.686	127.721	891.016	-0.7639	-0.0903	1.2716
	247	5.113	153.279	838.807	-0.6824	0.1944	1.2935
	255	-1.275	114.949	821.883	-0.6118	0.0429	0.9442
T6	239	-73.279	109.836	653.616	-0.4756	0.1032	0.8407
	250	-81.575	130.284	655.421	-0.4082	-0.0019	0.9248
	251	-79.816	176.258	737.109	-0.3163	0.0347	0.9955
T7	242	-80.144	173.716	753.916	-0.8662	0.0907	1.1425
	256	-84.292	160.936	618.566	-0.5958	-0.0647	0.8359
	259	-114.462	201.801	724.344	-0.4415	0.0706	0.8403
T8	246	-127.544	66.415	-246.833	0.4003	0.1243	-0.7979
	260	-154.062	58.747	-275.409	0.4996	0.1557	-0.7176
	248	-174.658	104.7360	-167.473	0.3509	0.1949	-0.5804

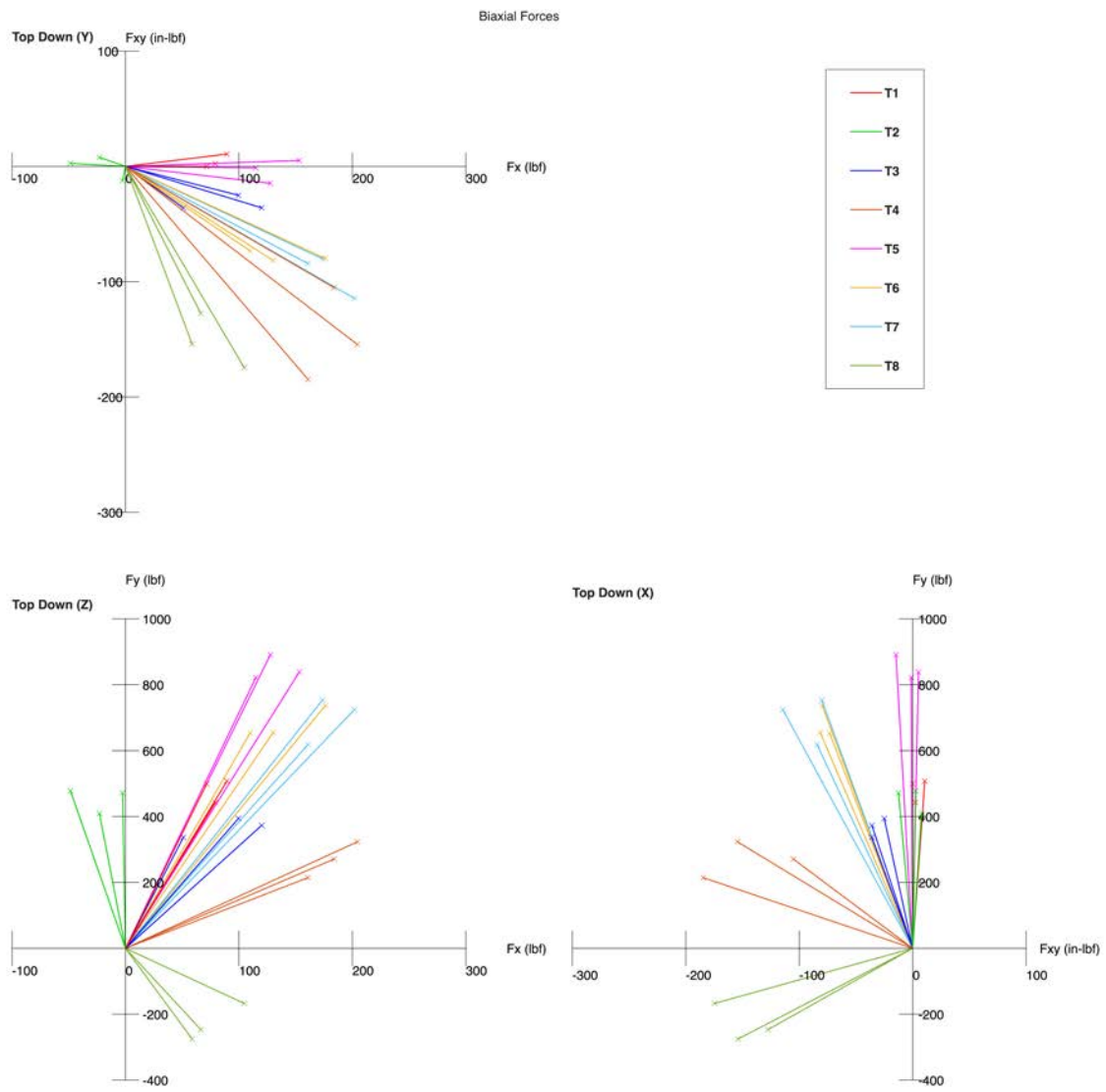


Figure 24: Biaxial sample test results showing the combinations of directional forces at failure across all eight test directions.

moments. The T2 direction showed similar but smaller magnitude of Fy forces but consisted of negative Fx forces in contrast to the T1 results. Similar to the T1 results, the Fxy moment results were near zero. For both T3 and T4, all Fx and Fy force values were positive, and the Fxy moments were negative. Force values for these two directions were also exceptionally precise. Both T5 and T6 showed positive Fx and Fy forces, with only T6 showing all negative Fxy moments. T5 consisted of mostly negative or near zero Fxy moments. The T7 and T8 directions resulted in negative Fxy moments and positive Fx forces. The T7 direction resulted in positive Fy forces while the T8 direction resulted in negative Fy forces.

Biaxial Breaking Patterns

Across all biaxial tests, the pattern in which they broke outlined around the shape of the $[\pm 45^\circ]_4$ fibers. The single notch samples seen in T1, T2, T3, and T4 all began failing at the endpoint of the notch. From there, a right angle of strain concentration would slowly propagate from the notch towards the edge opposite to the notch as more displacement magnitudes were applied (see Figure 25).

For the T5 and T6 test directions, a diagonal line of strain concentrations oriented opposite to the outer layer fiber directions would gradually increase as displacements were further applied (see Figure 26). From the diagonal strain concentrations, small perpendicular concentrations from the larger diagonal line would begin to form. These smaller diagonals, in contrast to the larger diagonal, are aligned with the fiber direction of the outer layer.

For the T7 and T8 test directions, the strain concentrations gradually appeared as a right triangle on one side of the notch, with the right angle orienting from the very center of the notch (see Figure 27). Once again, this failure pattern outlines the $[\pm 45^\circ]_4$ fiber directions that make up the biaxial samples. For the T7 test, the strain concentration was on the side in the direction of shear travel.

In contrast, the T8 direction displayed a strain concentration that occurred on the side

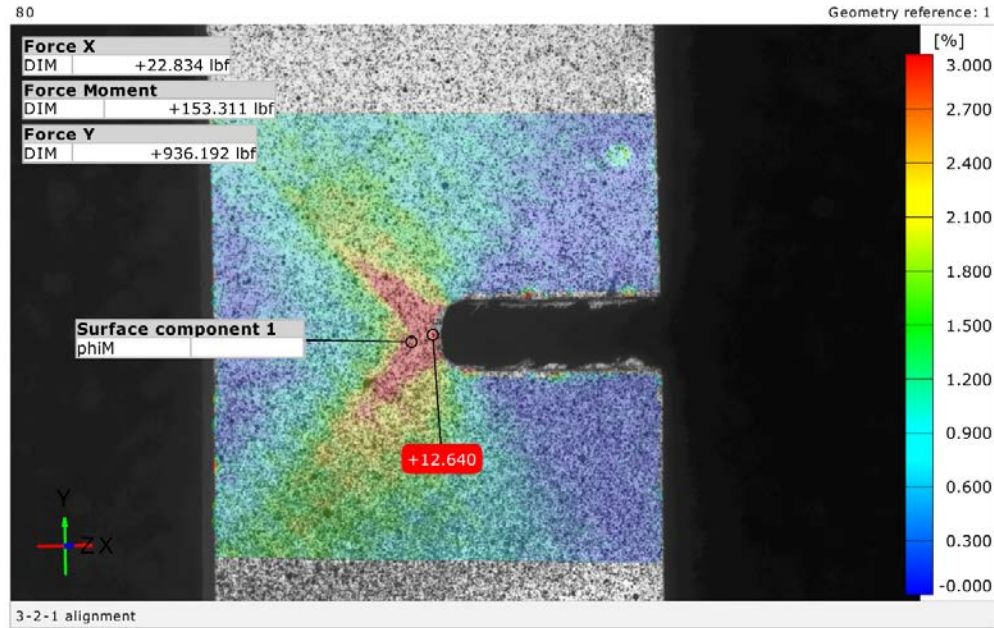


Figure 25: Biaxial T1 test representing the T1 through T4 failure pattern as seen through the ϕ_M strain concentrations in Aramis.

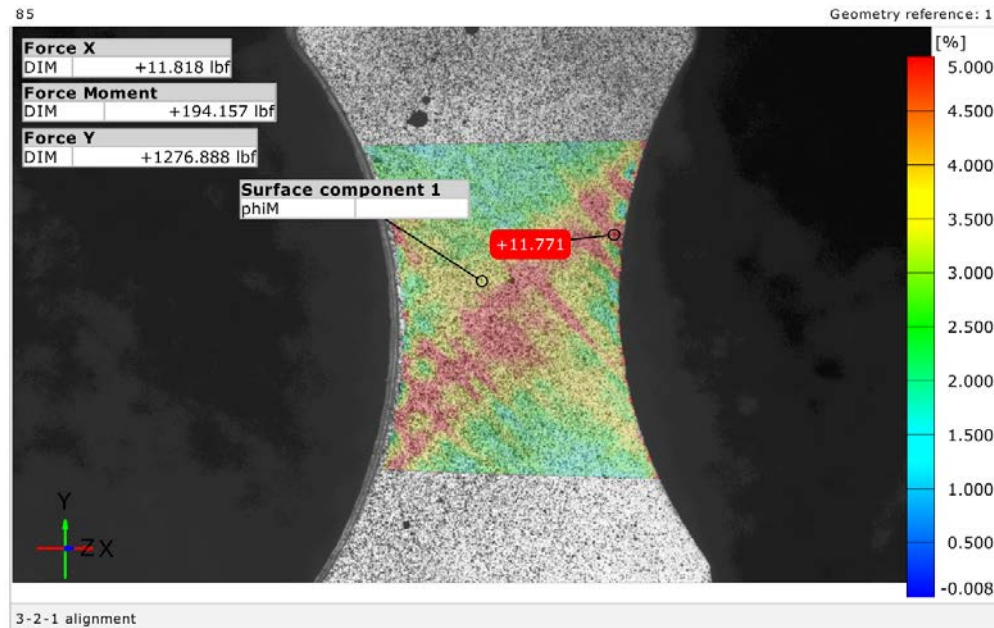


Figure 26: Biaxial T5 test representing the T5 and T6 failure pattern as seen through the ϕ_M strain concentrations in Aramis.

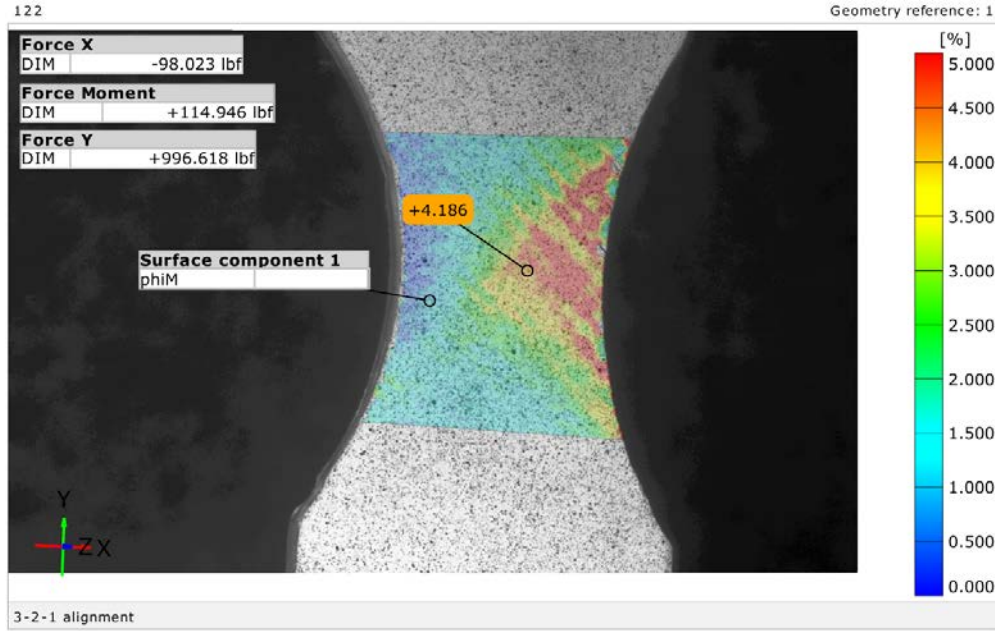


Figure 27: Biaxial T7 failure pattern as seen through the ϕ_M strain concentrations in Aramis with the direction of shear displacement acting on the top end of the coupon being oriented right as seen from the picture.

opposite to the direction of shear travel (see Figure 28). Among both directions, smaller grid-like strain concentrations can be observed within the larger strain concentration shape. These grid shapes align along the fiber directions of the $[\pm 45^\circ]_4$ that make up the biaxial sample.

Triaxial Coupon Results

The triaxial test results represent a combination of the uniaxial and biaxial results. The overall resulting strain and force plots from the triaxial tests appear to be a combination of the uniaxial and biaxial strain and force plots (see Figure 29). The $[\pm 45^\circ/0^\circ/\pm 45^\circ/0^\circ]_s$ layup that made up the triaxial samples is a combination of the $[0^\circ]_4$ uniaxial layup and the $[\pm 45^\circ]_4$ biaxial layup. This implies that the prediction of failure of a complex layup may be predicted through a mixture of the predicted failure of the simplified layups that make up the complex layup.

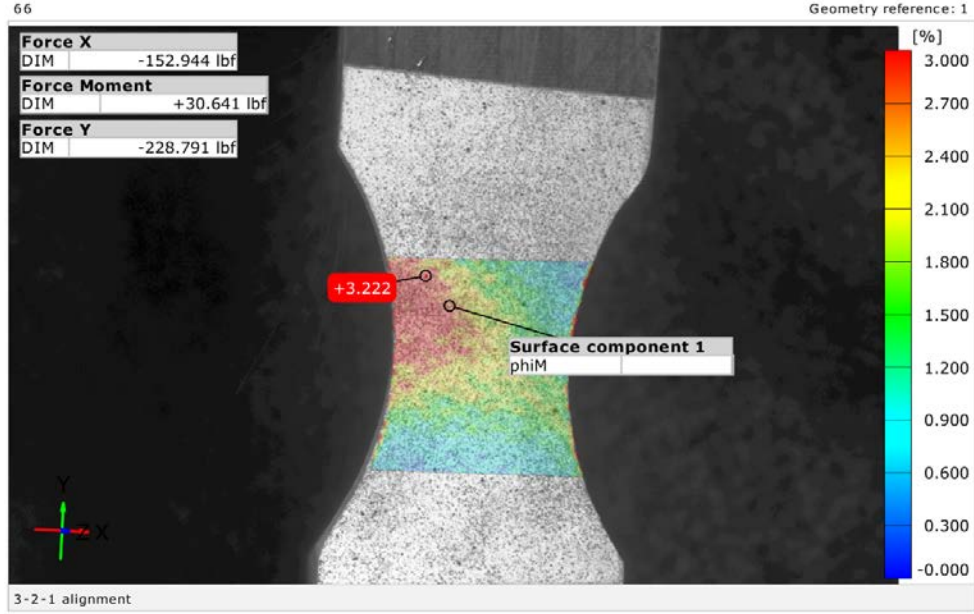


Figure 28: Biaxial T8 failure pattern as seen through the ϕ_M strain concentrations in Aramis with the direction of shear displacement acting on the top end of the coupon being oriented right as seen from the picture.

The T1 through T4 testing directions of the triaxial layup entirely consisted of the single 0.125 inch diameter notch. The T1 and T2 directions in bright red and bright green, respectively, displayed fair precision across the tests performed. The T1 strain results consisted of entirely positive ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strains. One test from the T1 direction displayed the smallest magnitude of all three directional strains. This test was also accompanied by the smallest resulting forces that led to failure of that sample, implying that a defect may have been present in that sample. The T2 tests displayed all positive ϵ_{yy} and ϵ_{xy} strain values. Where the T2 strain results differ from the T1 results is in ϵ_{xx} signage. Two of the three tests from T2 displayed near zero ϵ_{xx} values. The one T2 test that was not close to a zero ϵ_{xx} value was positive and was accompanied by the smallest ϵ_{yy} combination. This implies an inverse relationship between the ϵ_{xx} and ϵ_{yy} strain values. The T3 and T4 directions in dark blue and dark orange, respectively, displayed fair precision from testing. From the T3 tests, the resulting strains displayed exclusively positive ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} strain

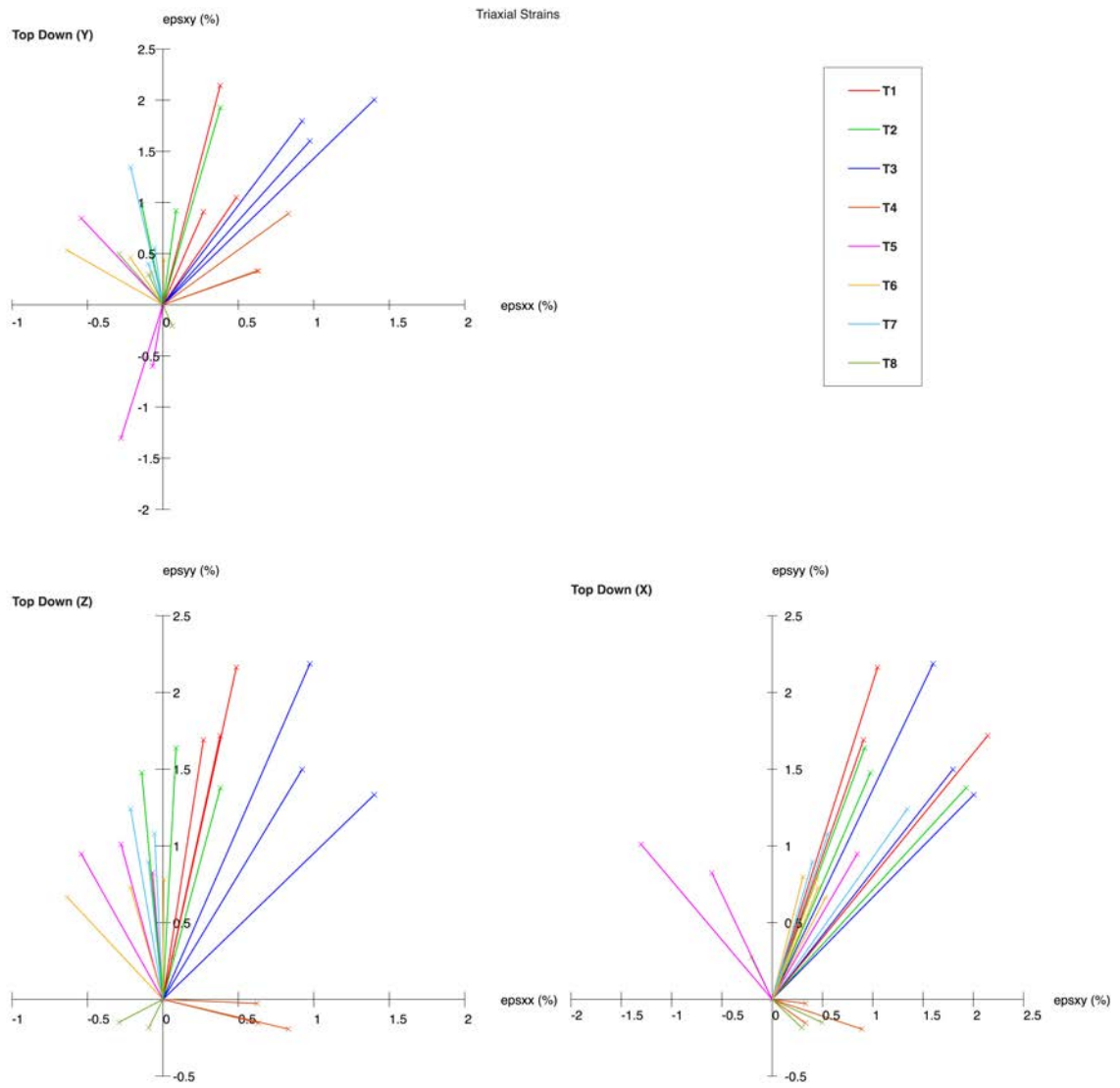


Figure 29: Triaxial sample test results showing the strain combinations at failure across all eight test direction.

values. One test displayed a considerably larger ϵ_{xx} strain value and was accompanied with the smallest ϵ_{yy} value. An inverse relationship is implied between the ϵ_{xx} and ϵ_{yy} values from these tests. The T4 direction produced all positive ϵ_{xx} and ϵ_{xy} strains, and all negative ϵ_{yy} strains. The T5 through T8 testing directions of the triaxial layup consisted of both the original and revised 2.00 inch diameter notch (seen in Figure 12). The T5 and T6 directions in bright pink and dark yellow, respectively, displayed good precision in their results. The T5 direction resulted in all negative ϵ_{xx} values, all positive ϵ_{yy} values, and both positive and negative ϵ_{xy} values. The ϵ_{xy} strain values were positive or negative based on which end of the coupon failed first. Across testing, either end of the coupon experienced FPF. Not all the T5 tests resulted in FPF on one end of the coupon every time, causing some sign difference among results for ϵ_{xy} . The T6 tests consisted of all negative ϵ_{xx} values, and all positive ϵ_{xy} and ϵ_{yy} values. The lower ϵ_{yy} values from the T6 tests resulted in greater ϵ_{xx} and ϵ_{xy} strain magnitude, displaying an inverse relationship. The T7 and T8 directions in light blue and dark green, respectively, displayed fair precision. The T7 results consisted of all negative ϵ_{xx} values and all positive ϵ_{yy} and ϵ_{xy} values. The resulting strain data suggests an unexpected direct relationship between the ϵ_{xx} , ϵ_{xy} , and ϵ_{yy} , prompting the concern for the integrity of this tests' data. The T8 test data consists of two tests showing negative ϵ_{xx} and ϵ_{yy} values with a positive ϵ_{xy} value. The remaining third test from T8 shows strain signage that is completely opposite to the other two tests. The magnitudes of all strain directions are similar for the T8 tests, but the signage difference calls to question the integrity of the outlying test's data. The raw data numbers for the triaxial samples are seen in Table 5.

The resulting forces that led to failure within the triaxial samples displayed very precise results that outlined a smooth shape within the scatter plots (see Figure 30).

The T1 and T2 directions in bright red and bright green, respectively, displayed great precision. The F_x and F_y forces were positive, and the F_{xy} moments hovered around zero for both T1 and T2 directions. One test from T2 displayed considerably less F_y forces than

Table 5: Triaxial sample results at failure showing the detailed combinations of loads and strains occurring at failure. Each coupon's associated notch dimensions are found in Appendix A.

Test	Sample	F_{xy} [in-lbf]	F_x [lbf]	F_y [lbf]	ϵ_{xx} [%]	ϵ_{xy} [%]	ϵ_{yy} [%]
T1	306	-5.427	229.961	606.361	0.2689	0.9088	1.6912
	321	7.983	252.904	917.520	0.4872	1.0485	2.1633
	324	1.282	311.650	777.993	0.3796	2.1431	1.7182
T2	307	10.546	43.433	601.574	0.0874	0.9200	1.6387
	312	-5.585	76.773	811.186	0.3809	1.9279	1.3778
	323	-5.105	2.570	465.703	-0.1401	0.9771	1.4762
T3	304	-90.362	268.227	621.526	0.9741	1.6006	2.1866
	308	-84.290	326.974	725.618	0.9231	1.7969	1.4983
	311	-48.691	255.452	602.033	1.4014	2.0046	1.3335
T4	309	-120.704	20.432	-123.694	0.6329	0.3302	-0.1547
	315	-124.213	40.885	-10.696	0.8316	0.8916	-0.1937
	325	-107.200	45.985	36.247	0.6237	0.3324	-0.0259
T5	334	-	-	1384.673	-0.2775	-1.3030	1.0105
	342	-	-	1018.586	-0.0679	-0.5993	0.8235
	344	-	-	1463.787	-0.5418	0.8465	0.9484
T6	352	-40.388	140.504	644.675	-0.0502	0.3698	0.9559
	332	-100.251	137.943	805.602	-0.2155	0.4594	0.7295
	341	-83.336	145.609	817.575	-0.6330	0.5320	0.6649
T7	337	-124.686	81.749	894.372	-0.0960	0.4016	0.8964
	328	-95.303	12.006	746.419	-0.0554	0.5551	1.0806
	360	-87.643	232.440	619.769	-0.2136	1.3439	1.2412
T8	340	-92.758	45.991	-68.808	-0.0942	0.2950	-0.1850
	348	-161.413	10.210	72.482	0.0620	-0.2066	0.2741
	349	-109.209	56.208	19.481	-0.2917	0.4957	-0.1500

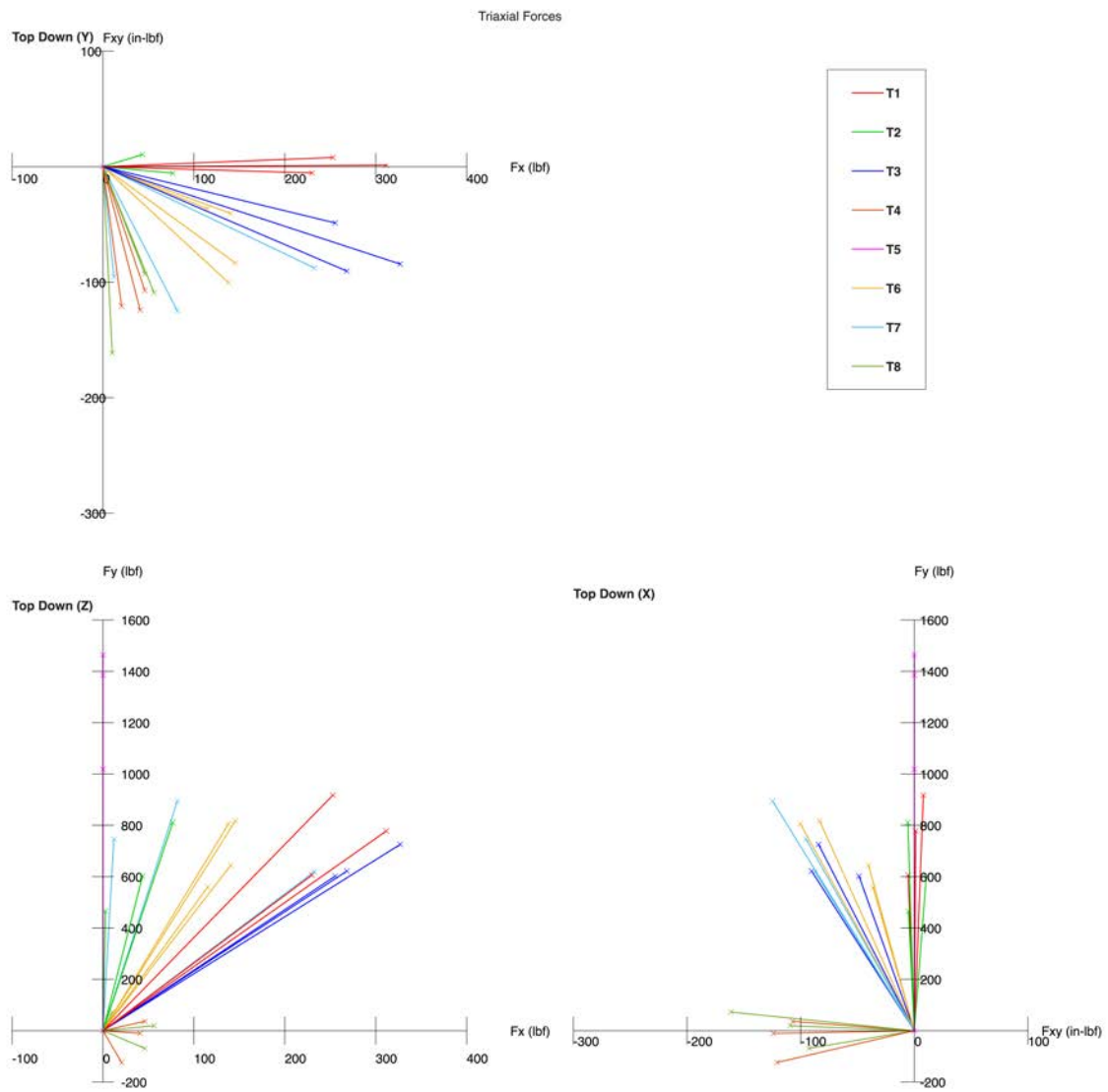


Figure 30: Triaxial sample test results showing the combinations of directional forces at failure across all eight test directions.

the other tests. This instance was accompanied by the only negative ϵ_{xx} strain value among the T1 and T2 tests, implying that a compressive ϵ_{xx} strain requires less Fy force to invoke failure. The T3 and T4 directions in dark blue and dark orange, respectively, displayed great precision in the resulting force data. For both the T3 and T4 directions, all resulting forces consisted of negative Fxy moments, and all positive Fx forces. For the T3 test direction, all Fy forces were positive. For the T4 direction, Fy forces varied between near-zero and prominently negative Fy forces. As seen in the uniaxial test of the same T4 direction, the magnitude of the Fy force experienced in the triaxial T4 test is considerably lower than the other test directions. The only positive Fy force from T4 was accompanied by the smallest ϵ_{yy} strain magnitude.

The T5 and T6 directions in bright pink and dark yellow, respectively, displayed great precision among the resulting force combinations. The T5 test direction for the triaxial layup was performed on the Instron instead of the IPL. This resulted in no recorded Fx and Fxy loads from the tests performed due to the Instron's single axis movement. All resulting Fy forces for both T5 and T6 were positive. All Fx forces were positive, and all Fxy moments were negative from the T6 tests. The T7 and T8 directions in light blue and dark green, respectively, showed good force data precision. For both T7 and T8, all Fxy moments were negative and all Fx forces were positive. All Fy forces were positive for T7, and the Fy forces hovered close to zero for the T8 tests. The triaxial T8 direction is the final instance of the recorded Fy forces being of considerably less magnitude than the other test directions that are not comprised of exclusive shear directionality.

Triaxial Breaking Patterns

As seen in the uniaxial and biaxial results, the strain concentrations revolved around the fiber shape of the triaxial layup. The T1, T2, and T3 test directions showed a strain concentration beginning at the endpoint of the notch (Figure 31). This strain concentration

gradually increased upwards to the top end of the coupon in the shape of the $[0^\circ]$ and $[\pm 45^\circ]$ fibers in the $[\pm 45^\circ/0^\circ/\pm 45^\circ/0^\circ]_s$ triaxial layup.

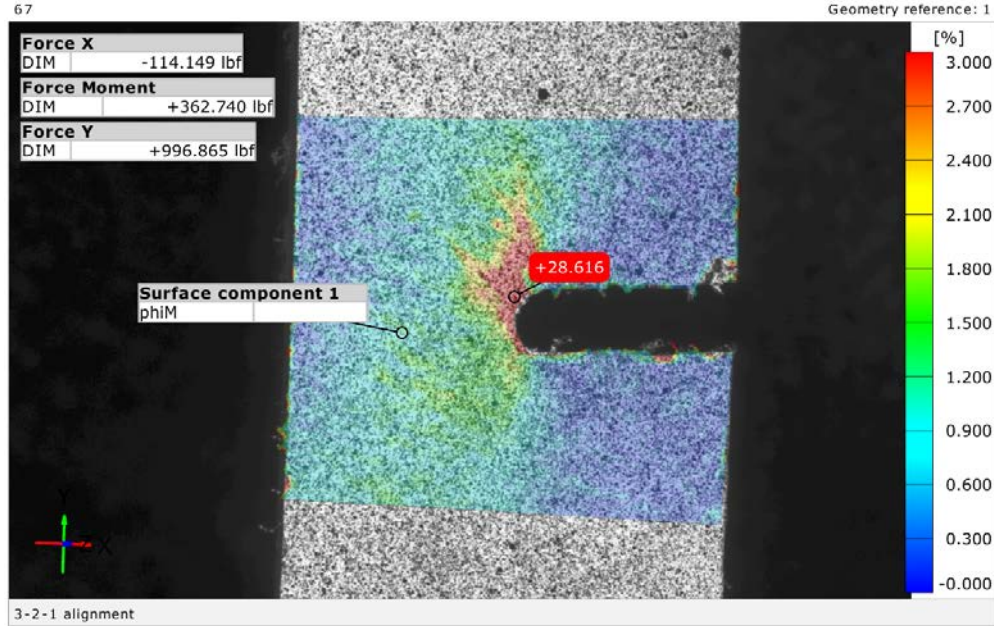


Figure 31: Triaxial T3 test representing the T1 through T4 failure pattern as seen through the ϕ_M strain concentrations in Aramis.

The T4 test direction caused some twisting about the length of the coupon (Figure 32). From this, the strain concentration began at the top end of the semicircular notch and gradually proceeded upwards towards the top end of the notch. This was the only test direction of all layups that displayed prominent twisting of the coupon.

The T5, T6, and T7 triaxial test directions resulted in a strain concentration resulting in crack propagation beginning at the upper endpoints of the notches on four points across the coupon (Figure 33), as seen in the uniaxial T5 and T6 tests (Figure 21). Unlike the uniaxial T5 and T6 tests, the shape of the crack seen in the T5, T6, and T7 triaxial tests mimicked the layup of the coupons (seen in Figure 31).

The T8 test direction for the triaxial layup displayed the most unique strain concentrations of the triaxial tests. The strain concentration formed a circular shape about the upper

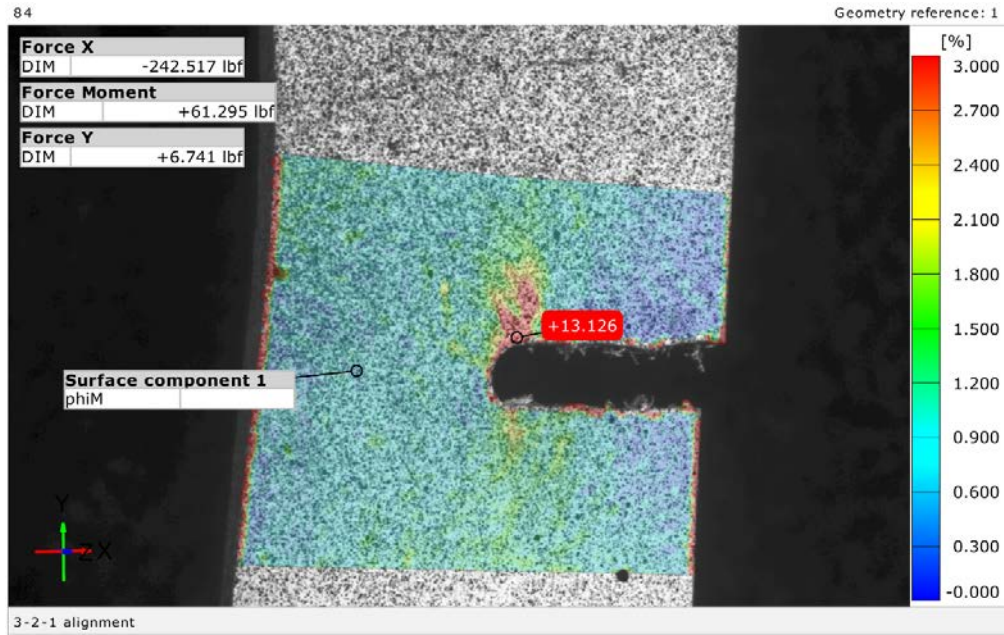


Figure 32: Triaxial T4 test representing the failure pattern as seen through the ϕ_M strain concentrations in Aramis.

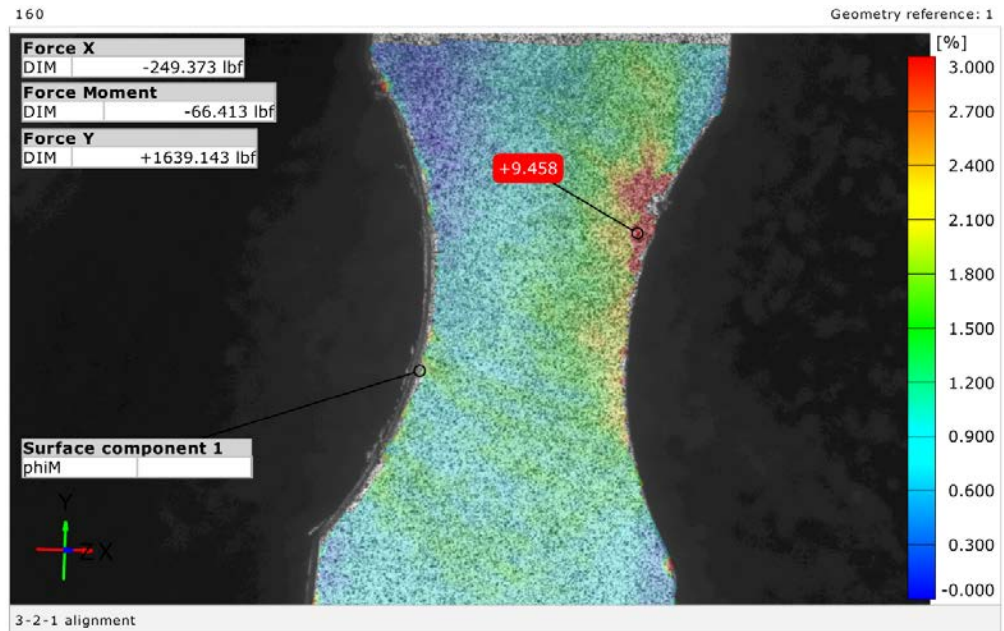


Figure 33: Triaxial T7 test representing the T5 through T7 failure pattern as seen through the ϕ_M strain concentrations in Aramis.

endpoint of the notch (Figure 34). This strain concentration expanded across the width of the coupon as the displacements acting on the coupon increased.

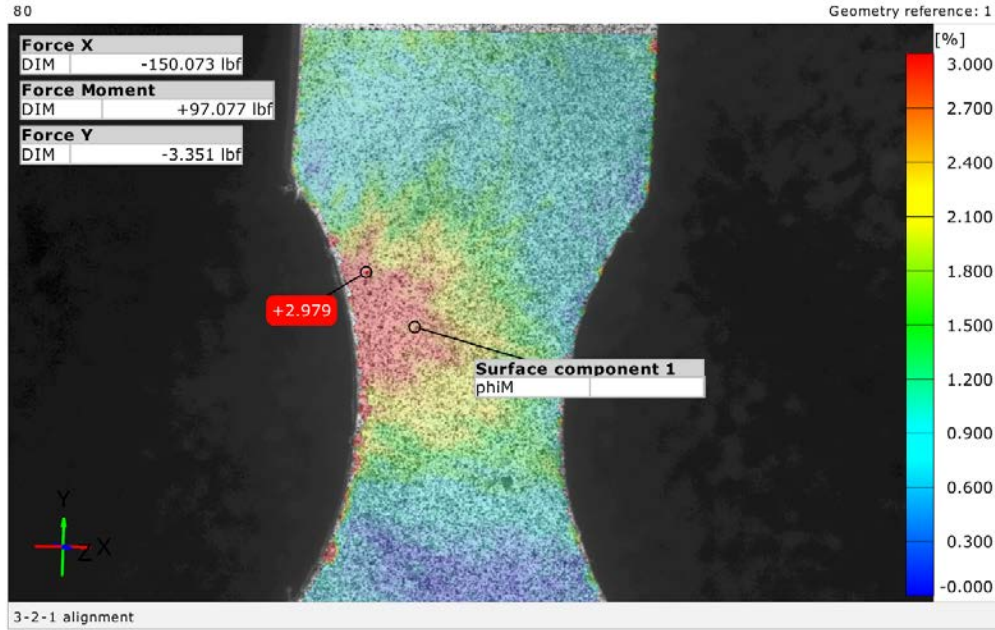


Figure 34: Triaxial T8 test representing the failure pattern as seen through the ϕ_M strain concentrations in Aramis.

Failure Model Application

Failure models of composites have evolved to become more complex in the pursuit of accuracy in their predictions [11] [24] [31]. To validate such increasingly complex models, increasingly complex data is required to validate it. The resulting data from these performed tests allow for the future computation of actual experienced stresses from the coupons with the recorded loading combinations per test along with the measured notch sizes of each tested coupon and layup fiber volume (Appendix A). FEA analyses of virtual coupons of the same dimensions as the measured notches subject to the same exact loading conditions of each coupon's test can calculate the experienced stress within a coupon of any given test. This data, paired with the recorded experienced strain data for that coupon, allow for the

tuning of proposed failure theories to fit the experimental results.

CONCLUSIONS

A testing list was given from SNL to complete a set of multiaxial destructive tests on uniaxial, biaxial, and triaxial fiberglass layups. With revisions made to invoke failure within the coupons while retaining the original set of displacement vectors, testing proceeded. The IPL was used to displace the coupons according to the revised testing list (Table 2), and the coupons were observed and recorded with the DIC to gather strain data. The Instron was used only when a given test was too strong for the IPL's capabilities, and if the test was instructed with exclusive y displacements.

The testing methodology using the IPL and DIC was first verified through the tensile test of copper 110 coupons. With the IPL and DIC, stress and strain data were gathered from several copper tensile tests. The stress-strain data was plotted in Excel, and the resulting stress-strain curve was analyzed to compare the material values of copper to the experimental values. Following accurate yield tensile strength and elastic modulus values, testing of fiberglass proceeded.

The uniaxial laminates were made with a $[0^\circ]_4$ layup, the biaxial laminates were made with a $[\pm 45^\circ]_4$ layup, and the triaxial laminates were made with a $[\pm 45^\circ/0^\circ/\pm 45^\circ/0^\circ]_s$ layup. All fiberglass layups were made with four plies to keep consistency between layups. Two notch geometries were cut into the fiberglass coupons: a single 0.125 inch notch, and a double 2.00 inch notch. The 2.00 inch notch, originally allowing 0.50 inches of material width, later included a revision that allowed for 0.25 inches of minimum material width. This revised notch was used in tests that were difficult for the IPL to break with the original 0.50 inch width at the notch present in the original 2.00 inch double notch.

Following the completion of the testing list, analysis of the resulting data consisted of a three-stage process. Initial data analysis began in Aramis, the DIC's software. Strain values were probed at the apparent ϕ_M strain concentrations observed on the sample. From this

probed strain, the ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} directional strain was probed at the same location on the sample as the probed ϕ_M value. The Fx , Fy , and Fxy load values during the test were also recorded and logged in Aramis. All strain and load values were then exported to Excel for failure analysis.

In Excel, all three loading values were plotted against the ϕ_M probed strain. The resulting plots were analyzed for the first instance nonlinearity was displayed. Once nonlinearity was determined, the ϵ_{xx} , ϵ_{yy} , ϵ_{xy} , Fx , Fy , and Fxy values at that determined instance were recorded. This process was repeated for every test performed. The recorded six values were then exported into MATLAB for the final part of the data analysis process.

The MATLAB code written extracted the six values at failure for every test performed. The stress and load values were kept separated. The strain values were then plotted in 3D space as a scatter plot, where the ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} values were plotted as x , y , and z coordinates, respectively. Similarly, the load values Fx , Fy , and Fxy were plotted as x , y , and z coordinates, respectively. Each layup consisted of a load and strain scatter plot. Each scatterplot was displayed as a three view, where each view was shown from the top-down perspective from each of the x , y , and z , axes.

The raw data for all test directions of each layup was saved in a table. This data includes the raw ϵ_{xx} , ϵ_{yy} , ϵ_{xy} , Fx , Fy , and Fxy values at failure for each sample, as well as which sample number was used to extract that data. Additionally, the raw coupon measurements for each tested sample were recorded. This includes the sample number, the test direction used for that sample, the date the sample was tested, as well as the measurements for the smallest cross-sectional area measured. Each layup in these tables was recorded with a fiber volume percentage for insight to the details of each layup.

Future Work

DIC Weaknesses in Computation

The instructed procedures with the DIC and the notch geometries used conflicted with the resulting data. Very rarely did failure within a sample begin away from the edge of the coupon. This led to strain concentrations occurring on locations of the coupon that the DIC could not always reliably measure. The biaxial tests mostly resulted in broad areas of strain concentrations that catered to the DIC's capabilities when probing the virtual surface, leading to the most consistent strain results of the three layups.

The small single notch samples caused great stress concentrations at the notch when displacements were applied and allowed a great surface area of the coupon to remain simultaneously. This combination caused failure within the coupons easier and caused the strain probing to be more reliable. This simultaneously catered to the strengths of the IPL and DIC. Failure at the notch was most notably poor for the double notch samples that included a $[0^\circ]$ aspect of the layup, as seen in the uniaxial and triaxial laminates. Future work regarding laminates including a $[0^\circ]$ lamina should not proceed with large double notch coupons due to the resulting strain concentrations remaining too close to the edge of the sample.

Additional Testing

As seen across the strain scatter plots of the uniaxial, biaxial, and triaxial layups, the triaxial scatter plot appears to be a combination of the uniaxial and biaxial strain scatter plots. Since the $[\pm 45^\circ/0^\circ/\pm 45^\circ/0^\circ]_s$ triaxial layup is a combination of both the $[0^\circ]_4$ uniaxial layup and the $[\pm 45^\circ]_4$ biaxial layup, determination of other complex laminates may be determined from the results of the isolated laminae that make it up. Testing of a layup made up of $[0^\circ/90^\circ]_4$ can be performed to contrast the previously performed $[\pm 45^\circ]_4$

biaxial tests, and the addition of $[30^\circ]$ laminae can help identify the fiber behaviors when oriented between the $[0^\circ]$ and $[45^\circ]$ laminae tested in this study.

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APPENDICES

APPENDIX A

COUPON MEASUREMENT TABLES

Table 6: Measurements of the smallest cross-section at the notch, date and time of when testing occurred, and associated fiber volume percentage for every successful uniaxial coupon test.

Uniaxial Fiber Volume				52.12 %	
SINGLE NOTCH					
SN	Neck Width [in]	Thickness [in]	X-Sec Area [in ²]	Test	Date/Time
117	0.5120	0.1080	0.055296	T1	11/6/2024 10:32
118	0.5285	0.1100	0.058135	T1	11/5/2024 12:52
119	0.5095	0.1055	0.053752	T1	6/21/2024 14:14
111	0.4995	0.1050	0.052448	T2	11/6/2024 13:57
115	0.5090	0.1050	0.053445	T2	11/5/2024 13:02
116	0.5130	0.1080	0.055404	T2	7/15/2024 11:35
124	0.5120	0.1065	0.054528	T2	11/6/2024 10:51
114	0.5090	0.1100	0.055990	T3	7/11/2024 12:18
122	0.5065	0.1075	0.054449	T3	7/11/2024 12:27
126	0.5180	0.1090	0.056462	T3	7/11/2024 12:00
112	0.5130	0.1075	0.055148	T4	11/6/2024 11:02
120	0.5150	0.1035	0.053303	T4	7/10/2024 12:00
129	0.5100	0.1085	0.055335	T4	7/10/2024 13:15
DOUBLE NOTCH					
134	0.3440	0.1075	0.036980	T5	11/22/2024 14:07
140	0.3445	0.1055	0.036345	T5	11/22/2024 13:58
142	0.3455	0.1065	0.036796	T5	11/22/2024 14:03
138	0.5520	0.1075	0.059340	T6	7/12/2024 10:45
153	0.5710	0.1050	0.059955	T6	7/12/2024 11:18
176	0.2880	0.1005	0.028944	T6	2/4/2025 10:19
135	0.5650	0.1050	0.059325	T8	7/11/2024 13:05
144	0.5560	0.1090	0.060604	T8	7/11/2024 13:21
155	0.5520	0.1055	0.058236	T8	7/11/2024 12:45

Table 7: Measurements of the smallest cross-section at the notch, date and time of when testing occurred, and associated fiber volume percentage for every successful biaxial coupon test.

Biaxial Fiber Volume				51.59 %	
SINGLE NOTCH					
SN	Neck Width [in]	Thickness [in]	X-Sec Area [in ²]	Test	Date/Time
216	0.4970	0.1000	0.049700	T1	7/15/2024 12:05
224	0.4990	0.1000	0.049900	T1	7/15/2024 12:00
227	0.5030	0.0980	0.049294	T1	7/15/2024 12:10
215	0.5035	0.0925	0.046574	T2	7/15/2024 12:17
222	0.4945	0.0965	0.047719	T2	7/15/2024 12:27
226	0.5000	0.0965	0.048250	T2	7/15/2024 12:30
209	0.5030	0.0955	0.048037	T3	7/15/2024 13:35
213	0.4945	0.0970	0.047967	T3	7/15/2024 13:28
219	0.4960	0.0935	0.046376	T3	7/15/2024 13:21
202	0.5035	0.0955	0.048084	T4	7/16/2024 12:13
203	0.5030	0.0935	0.047031	T4	7/16/2024 12:07
225	0.4990	0.0995	0.049651	T4	7/16/2024 12:26
DOUBLE NOTCH					
244	0.5535	0.0995	0.055073	T5	7/16/2024 13:14
247	0.5655	0.0975	0.055136	T5	7/16/2024 13:20
255	0.5610	0.0970	0.054417	T5	7/16/2024 13:22
239	0.5655	0.0905	0.051178	T6	7/17/2024 12:59
250	0.5460	0.0930	0.050778	T6	7/17/2024 11:05
251	0.5595	0.0955	0.053432	T6	7/17/2024 13:04
242	0.5535	0.0990	0.054797	T7	7/17/2024 13:12
256	0.5575	0.0945	0.052684	T7	7/17/2024 13:21
259	0.5600	0.0975	0.054600	T7	7/17/2024 13:27
246	0.5510	0.1000	0.055100	T8	7/25/2024 12:19
248	0.5520	0.1005	0.055476	T8	11/7/2024 11:08
260	0.5640	0.0990	0.055836	T8	7/25/2024 12:24

Table 8: Measurements of the smallest cross-section at the notch, date and time of when testing occurred, and associated fiber volume percentage for every successful triaxial coupon test.

Triaxial Fiber Volume				42.45 %	
SINGLE NOTCH					
SN	Neck Width [in]	Thickness [in]	X-Sec Area [in ²]	Test	Date/Time
306	0.5030	0.0660	0.033198	T1	7/22/2024 12:14
321	0.5210	0.0635	0.033084	T1	7/22/2024 12:24
324	0.5120	0.0665	0.034048	T1	7/22/2024 12:15
307	0.5135	0.0660	0.033891	T2	7/22/2024 13:18
312	0.5060	0.0640	0.032384	T2	7/22/2024 13:13
323	0.5115	0.0630	0.032225	T2	7/22/2024 13:08
304	0.5030	0.0650	0.032695	T3	7/23/2024 12:00
308	0.5115	0.0675	0.034526	T3	7/23/2024 11:50
311	0.5120	0.0605	0.030976	T3	7/23/2024 11:56
309	0.5105	0.0645	0.032927	T4	7/23/2024 12:12
315	0.5060	0.0620	0.031372	T4	7/23/2024 12:18
325	0.5110	0.0605	0.030916	T4	7/22/2024 12:06
DOUBLE NOTCH					
334	0.3490	0.0630	0.021987	T5	11/22/2024 13:01
342	0.3480	0.0640	0.022272	T5	11/22/2024 13:34
344	0.3500	0.0670	0.023450	T5	11/22/2024 13:54
332	0.5645	0.0705	0.039797	T6	7/24/2024 13:36
341	0.5500	0.0665	0.036575	T6	7/24/2024 13:40
352	0.2985	0.0635	0.018955	T6	2/26/2025 13:15
328	0.5380	0.0670	0.036046	T7	7/25/2024 11:37
337	0.5715	0.0650	0.037148	T7	7/25/2024 11:42
360	0.2630	0.0615	0.016175	T7	2/26/2025 13:35
340	0.5660	0.0685	0.038771	T8	7/25/2024 12:07
348	0.5390	0.0655	0.035305	T8	7/25/2024 11:57
349	0.5490	0.0605	0.033215	T8	7/25/2024 12:12

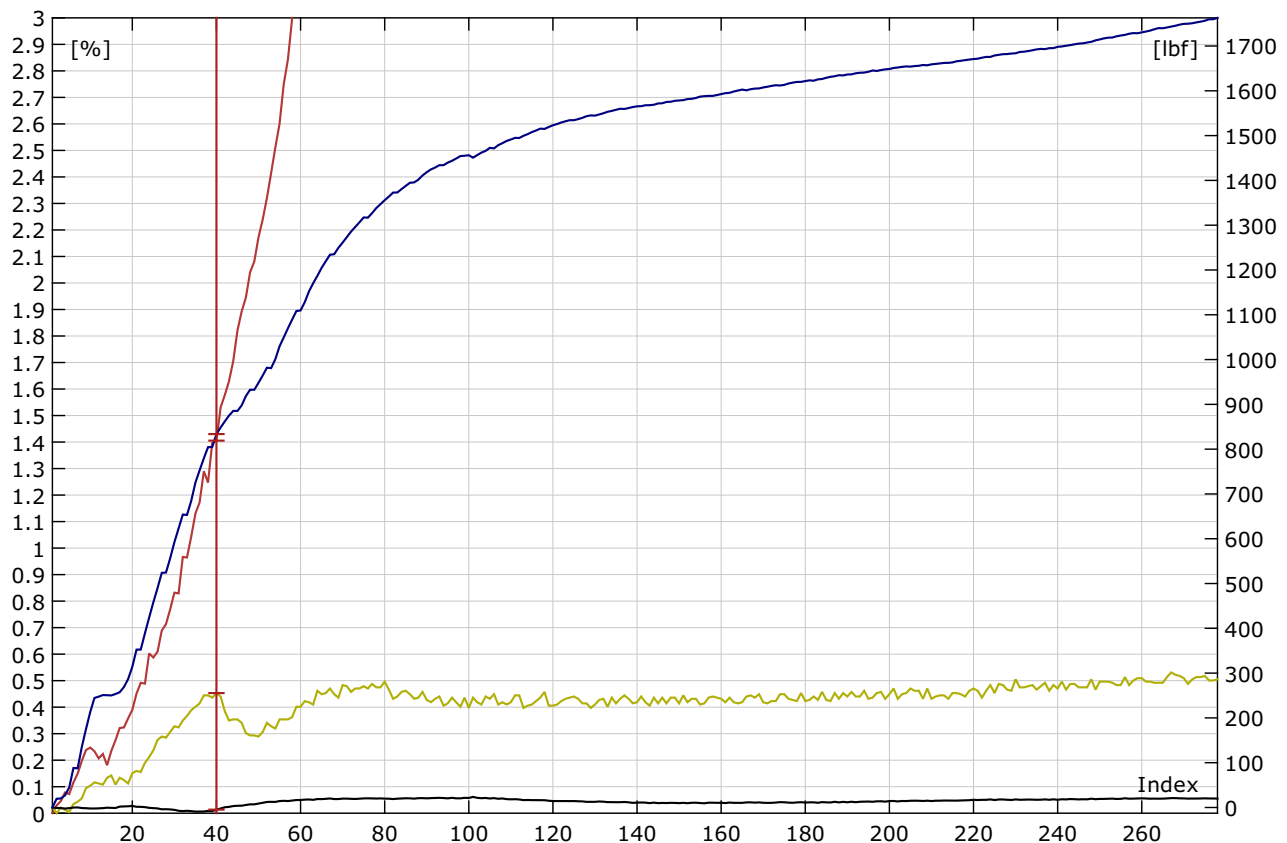
APPENDIX B

ARAMIS REPORT PAGES

Uniaxial T1 Failure Example (Sample 117)

40

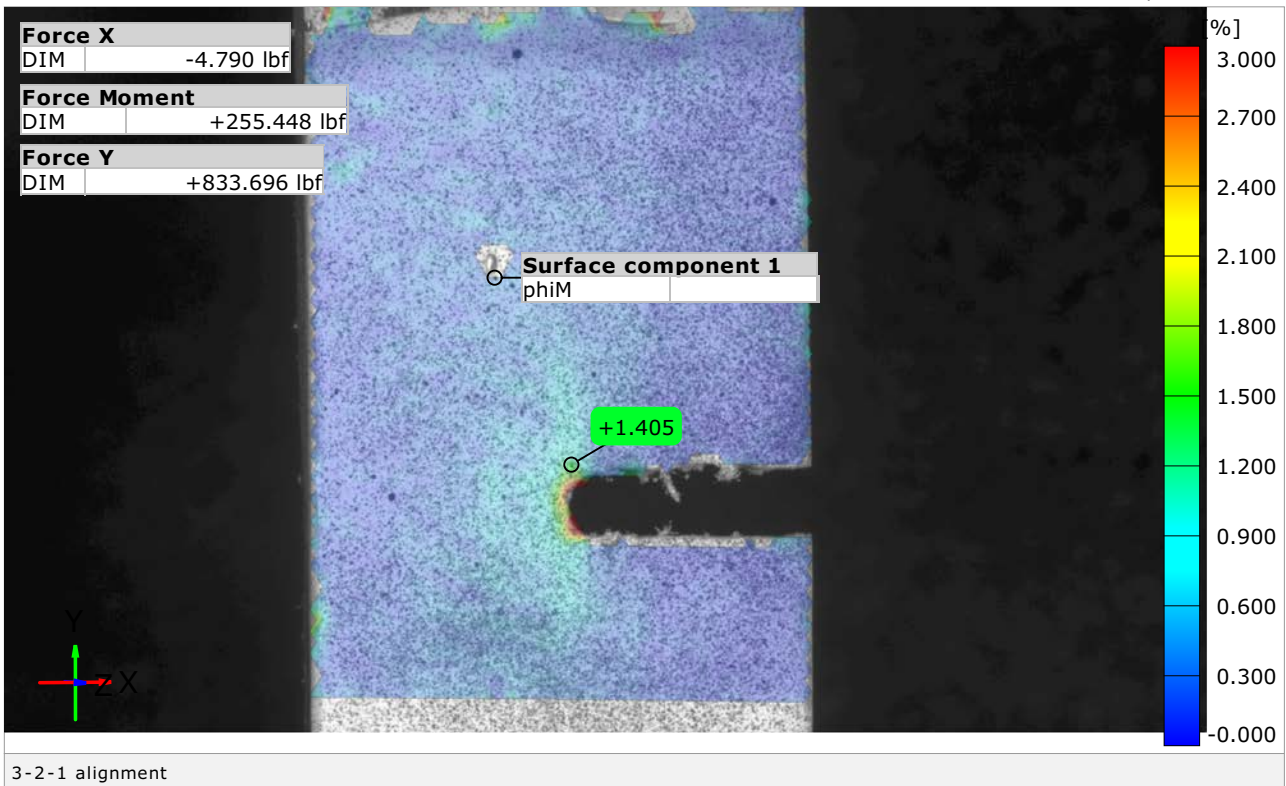
Geometry reference: 1



Uniaxial T1 Further Failure Example (Sample 117)

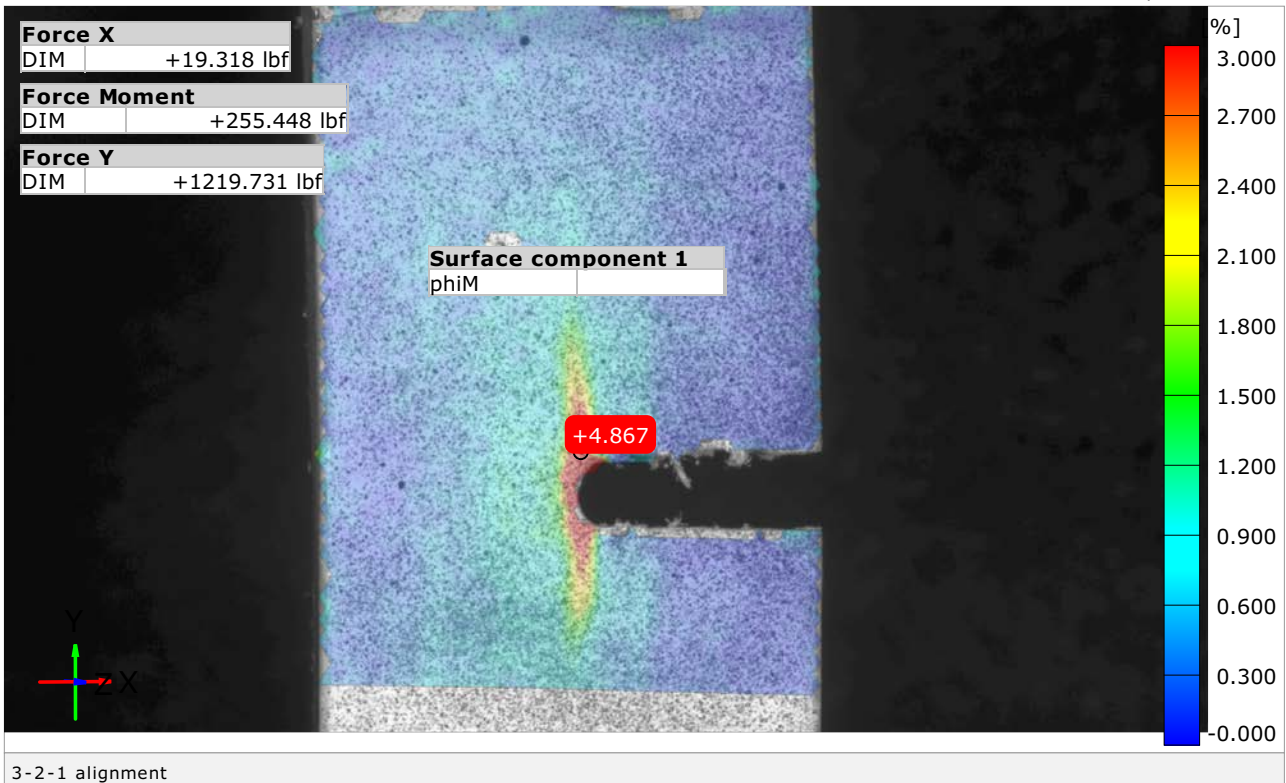
40

Geometry reference: 1



66

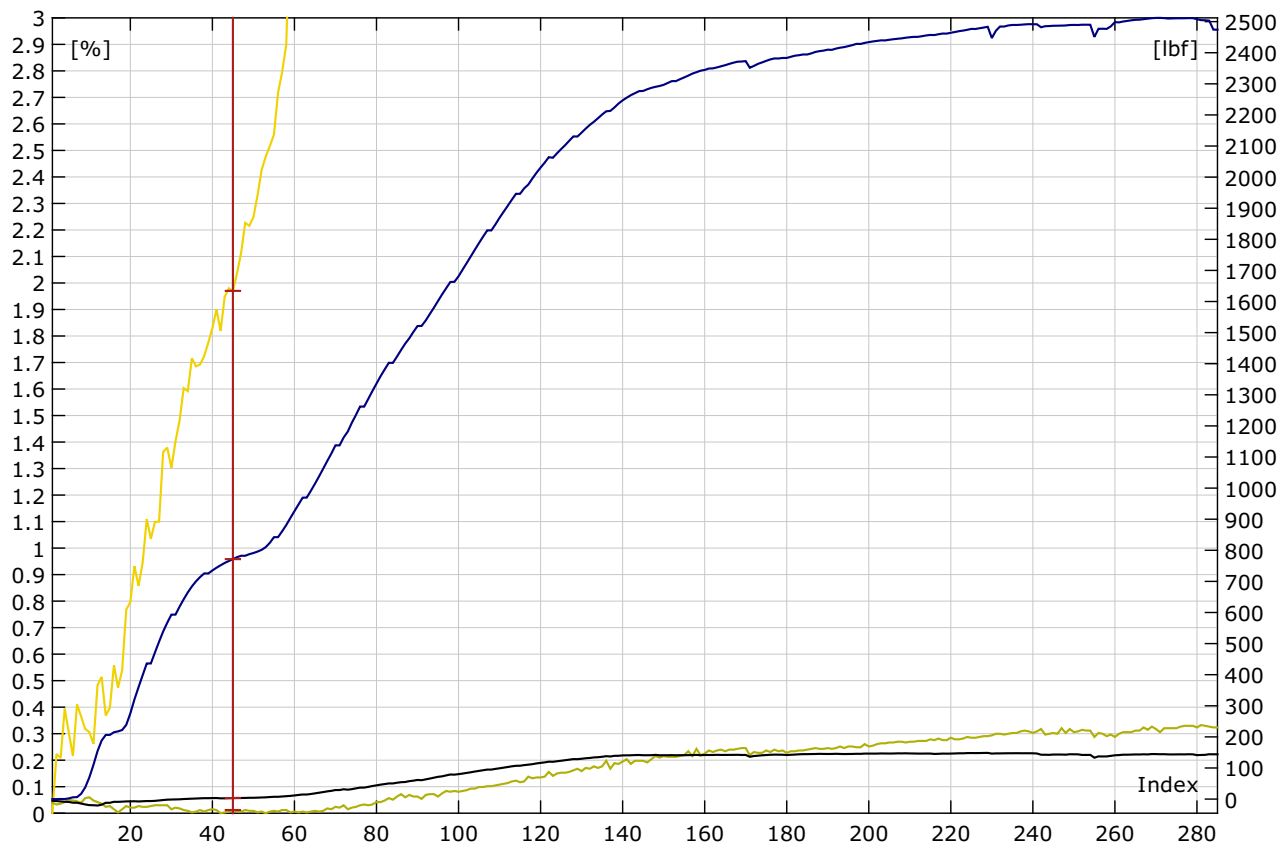
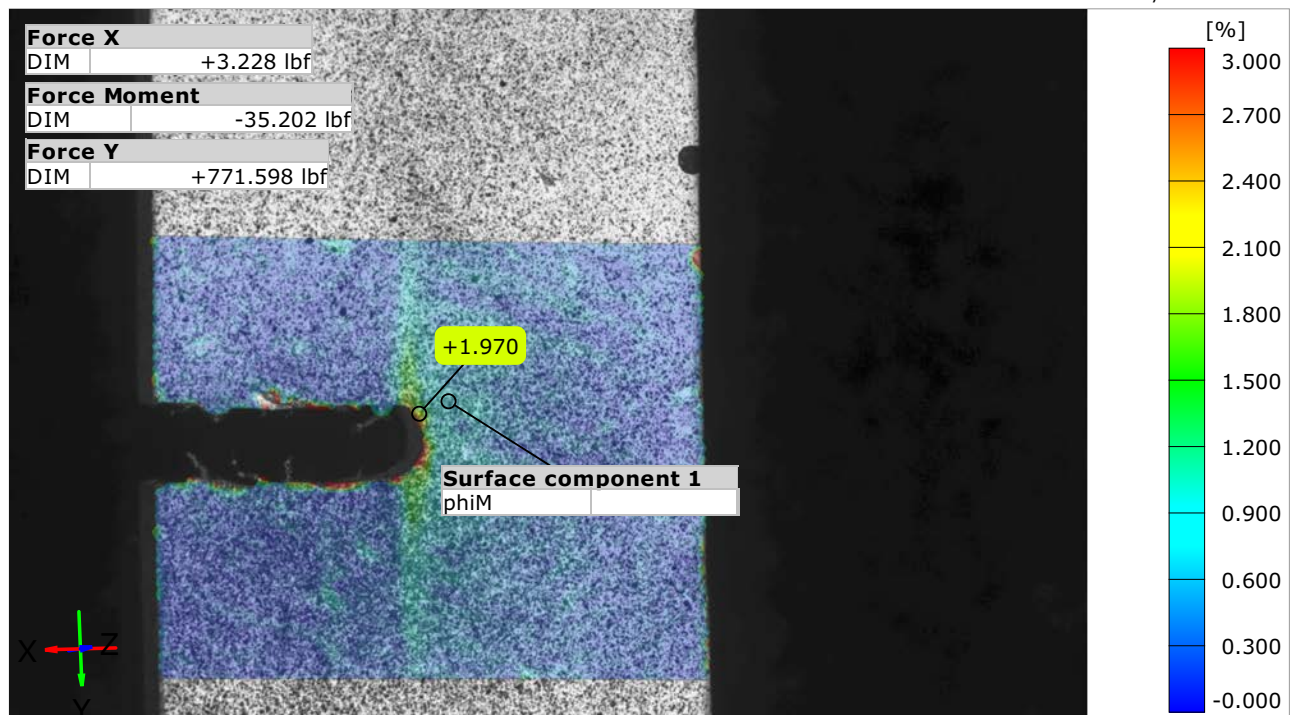
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Uniaxial T2 Failure Example (Sample 116)

45

Geometry reference: 1



3-2-1 alignment

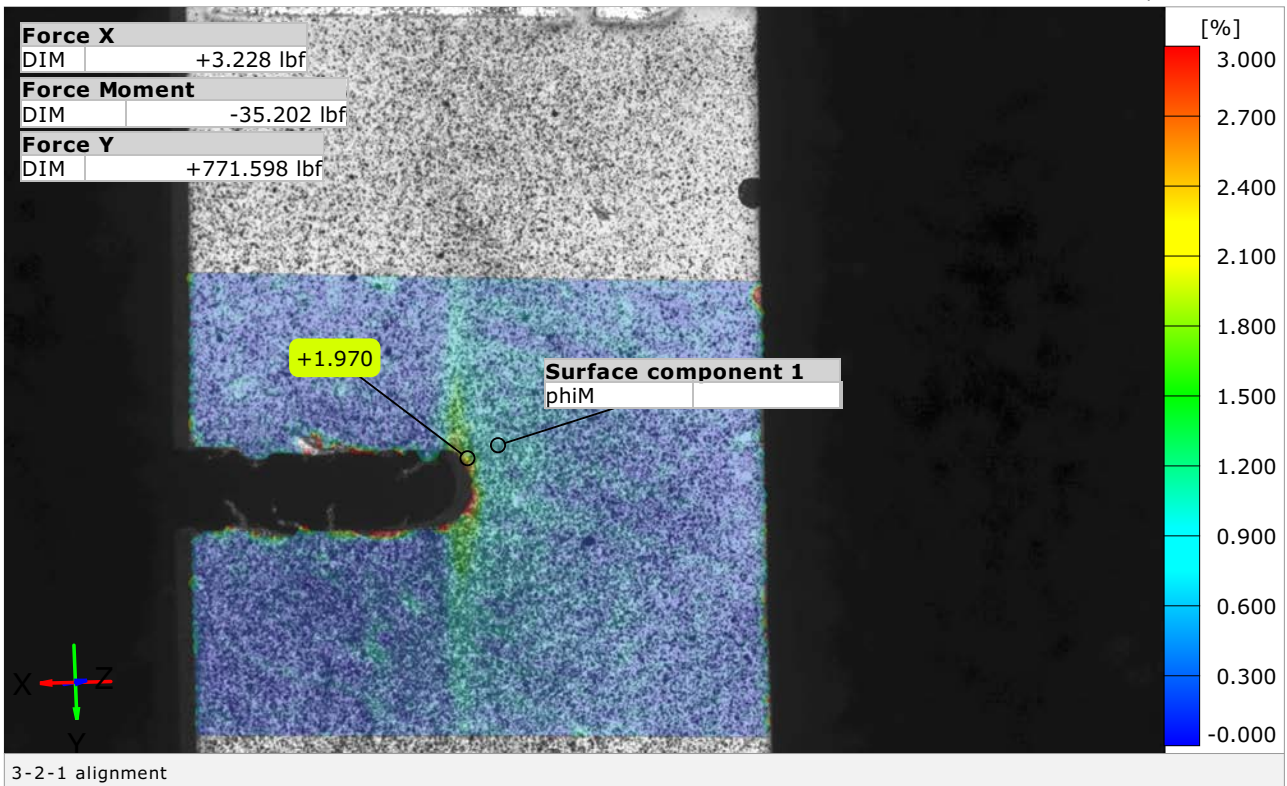
15.07.2024

1/2

Uniaxial T2 Further Failure Example (Sample 116)

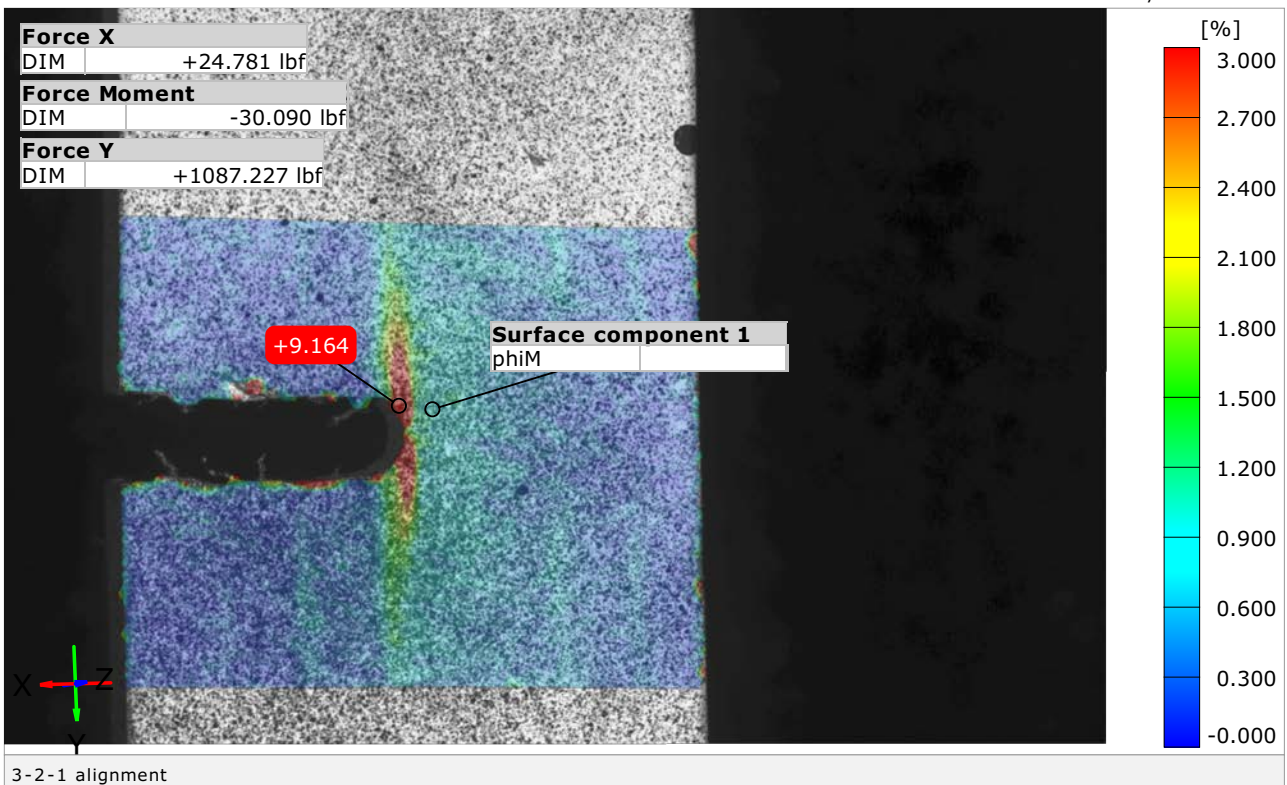
45

Geometry reference: 1



68

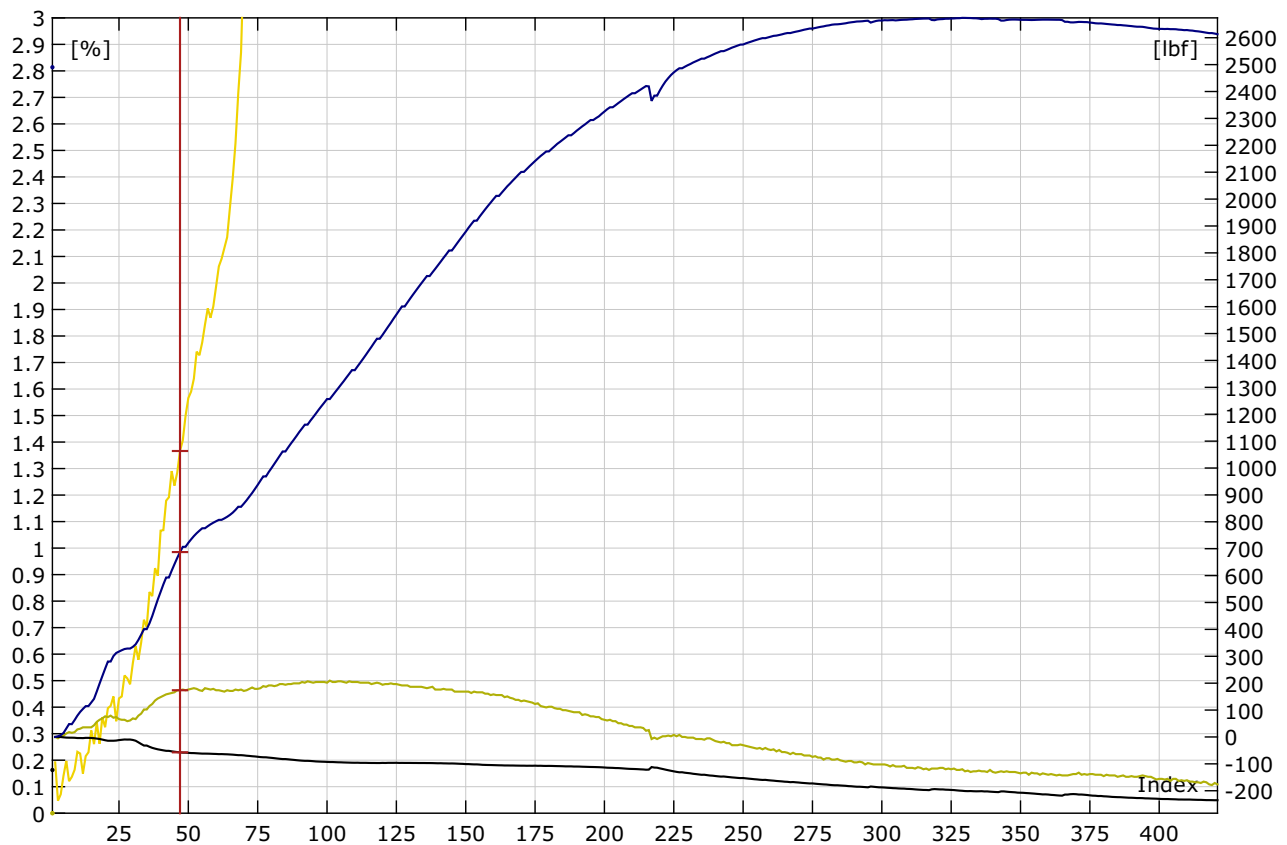
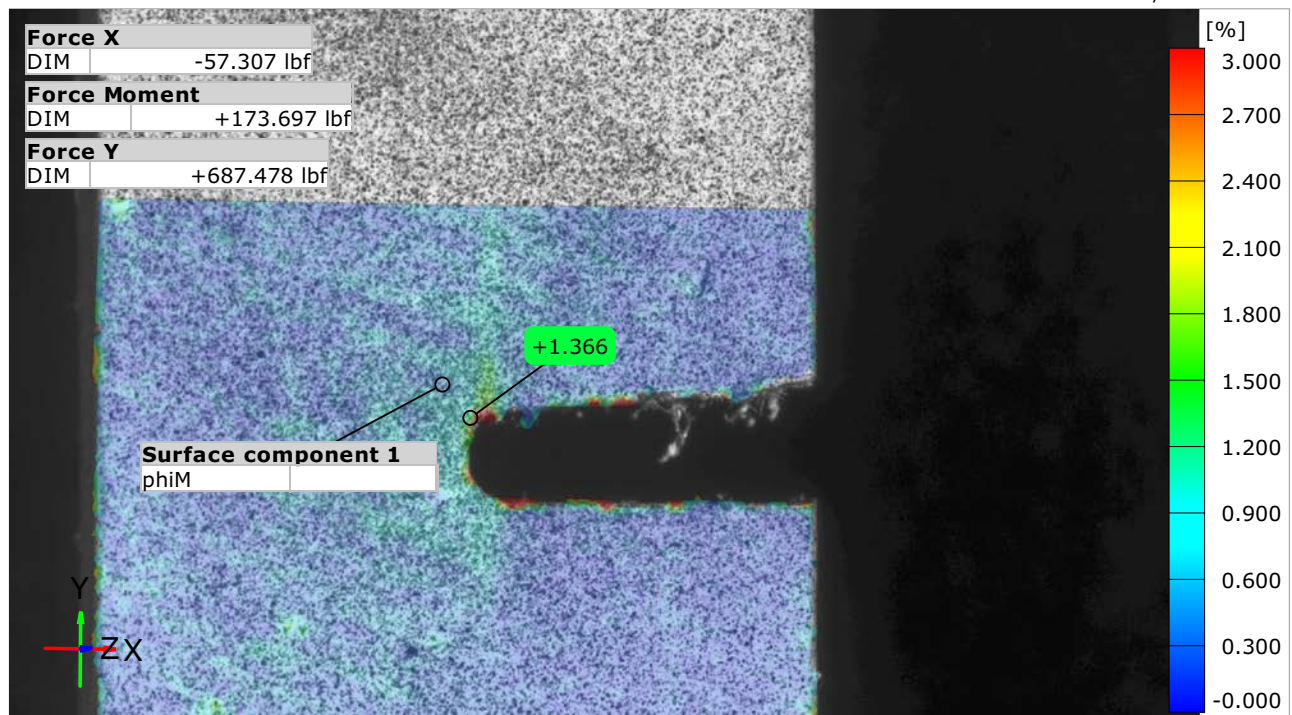
Geometry reference: 1



Uniaxial T3 Failure Example (Sample 114)

47

Geometry reference: 1



3-2-1 alignment

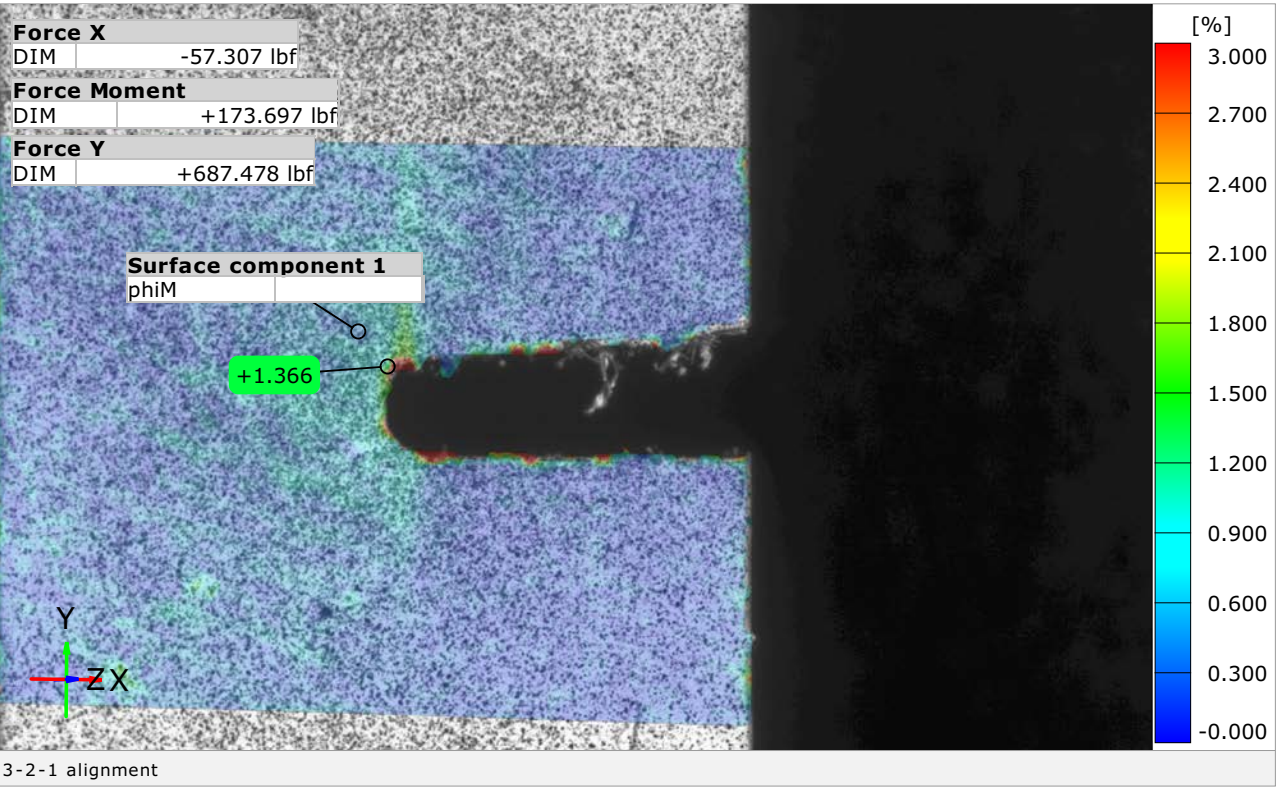
11.07.2024

1/2

Uniaxial T3 Further Failure Example (Sample 114)

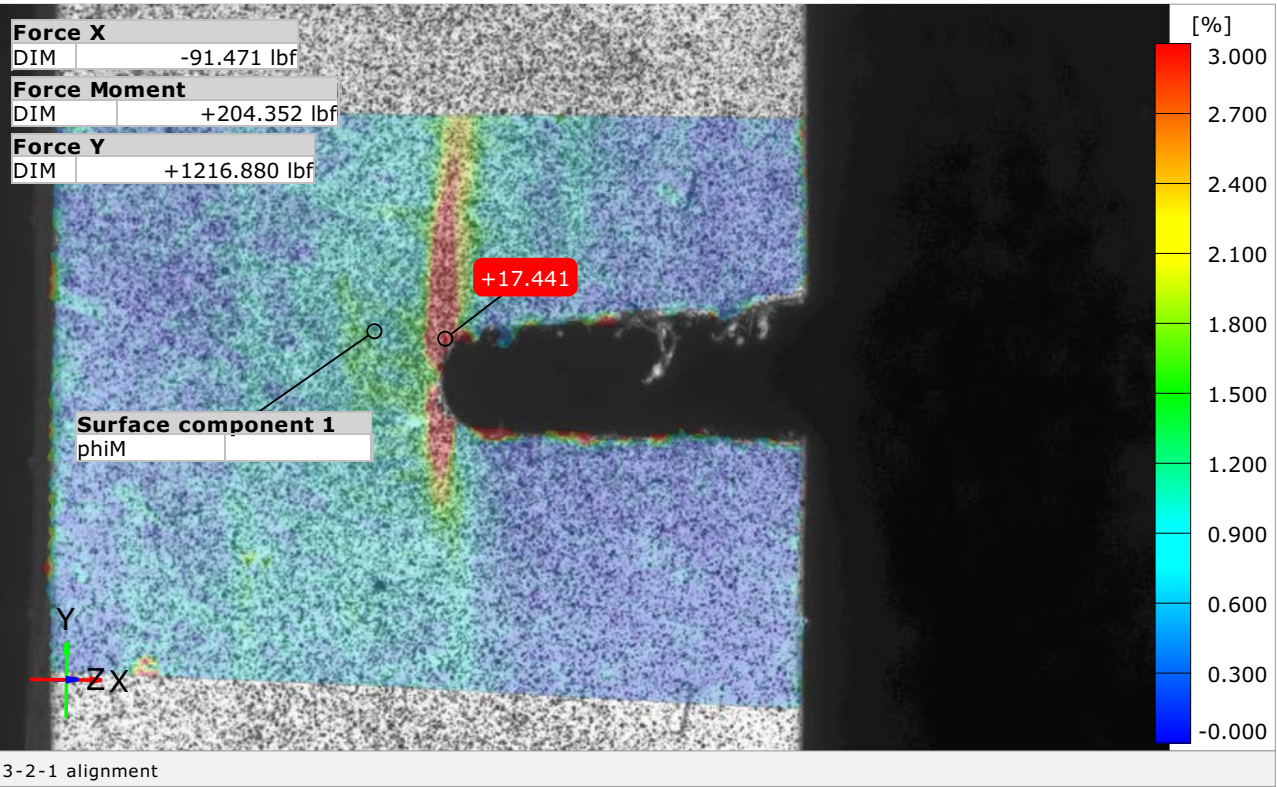
47

Geometry reference: 1



97

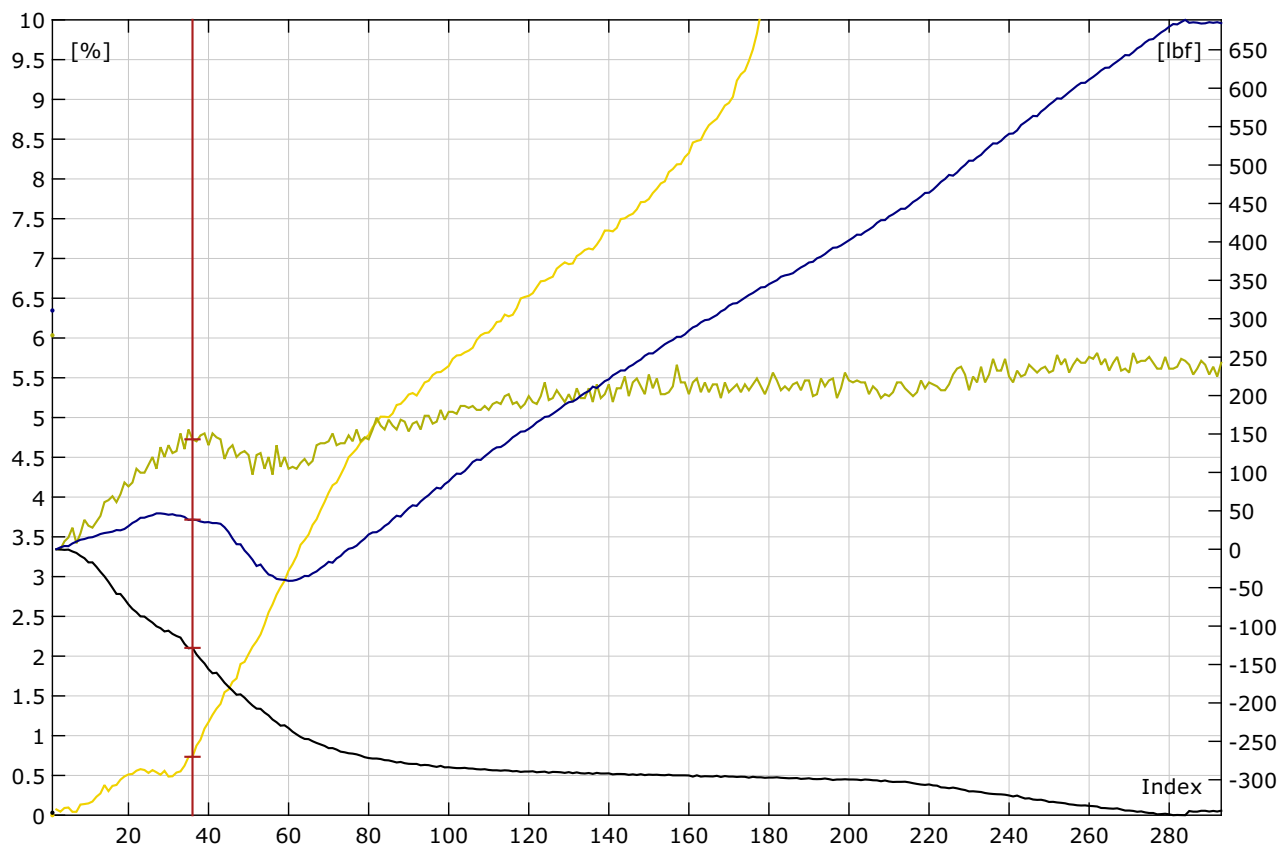
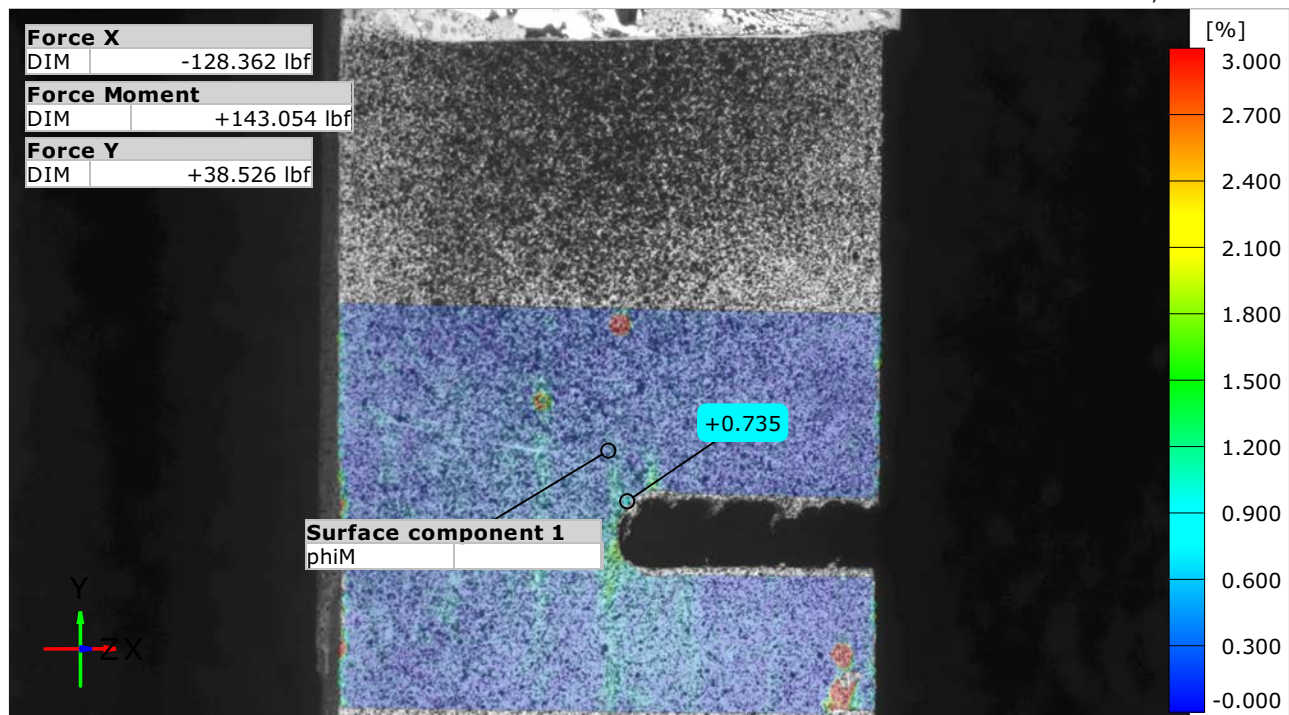
Geometry reference: 1



Uniaxial T4 Failure Example (Sample 120)

36

Geometry reference: 1



3-2-1 alignment

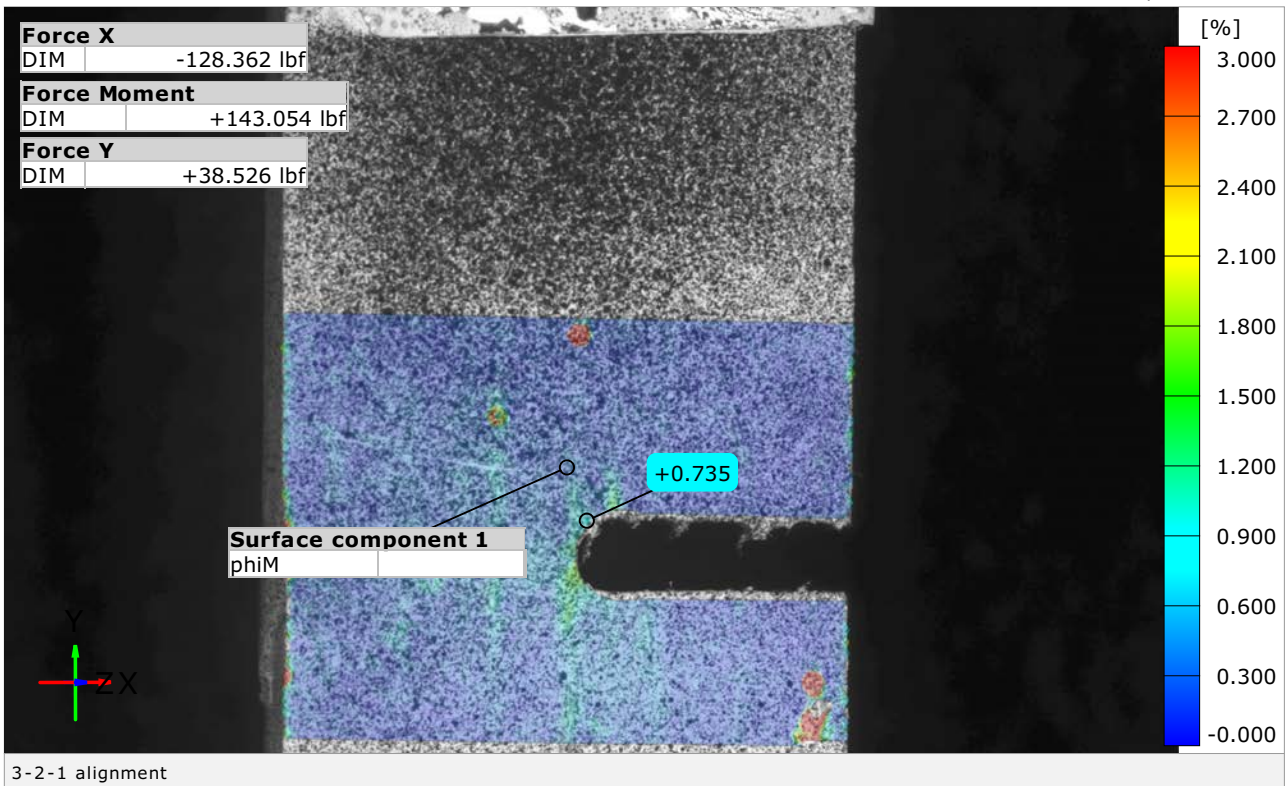
10.07.2024

1/2

Uniaxial T4 Further Failure Example (Sample 120)

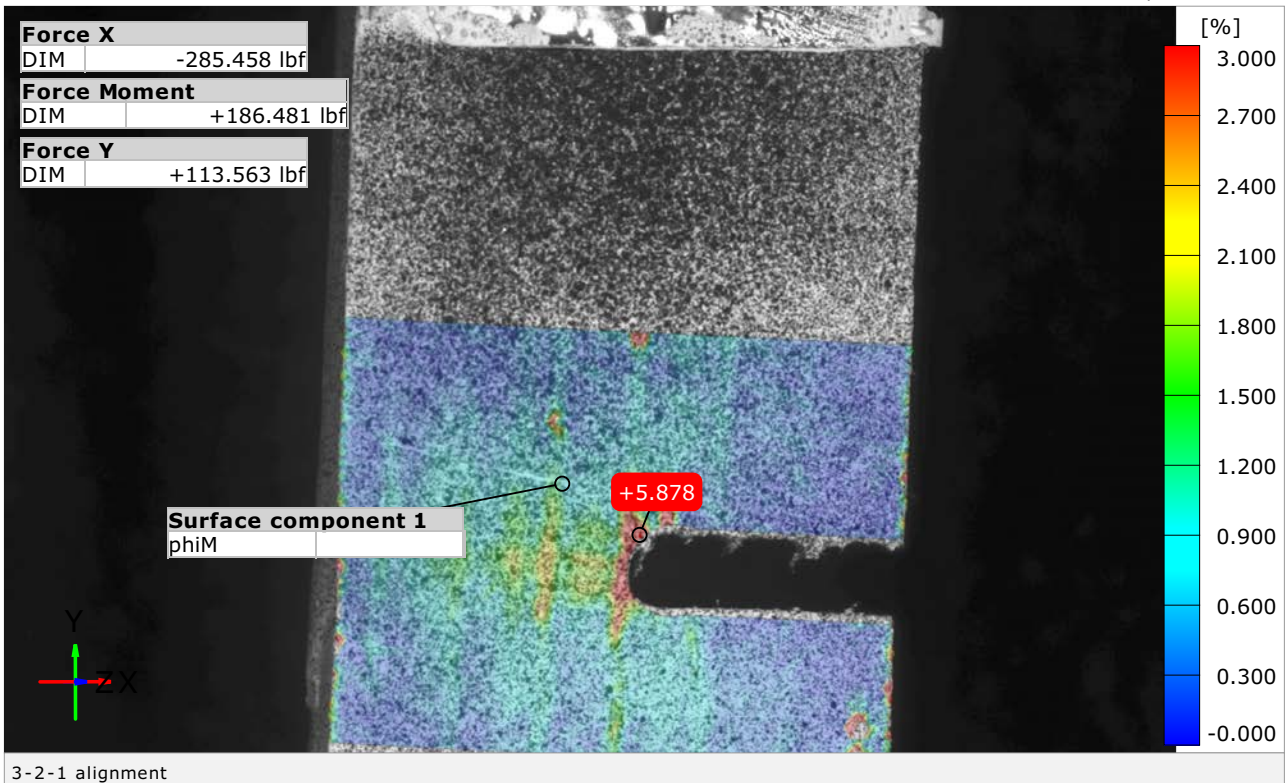
36

Geometry reference: 1



106

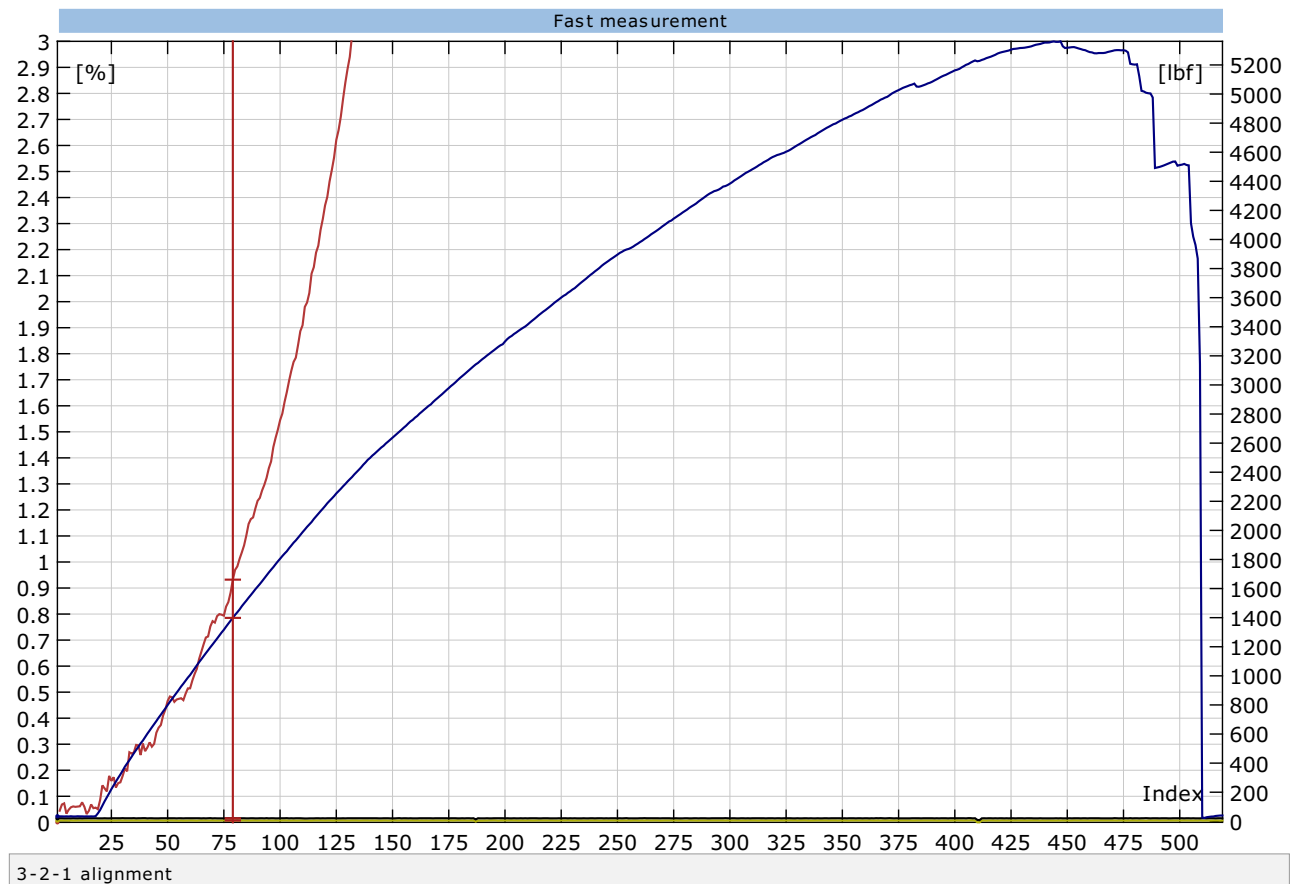
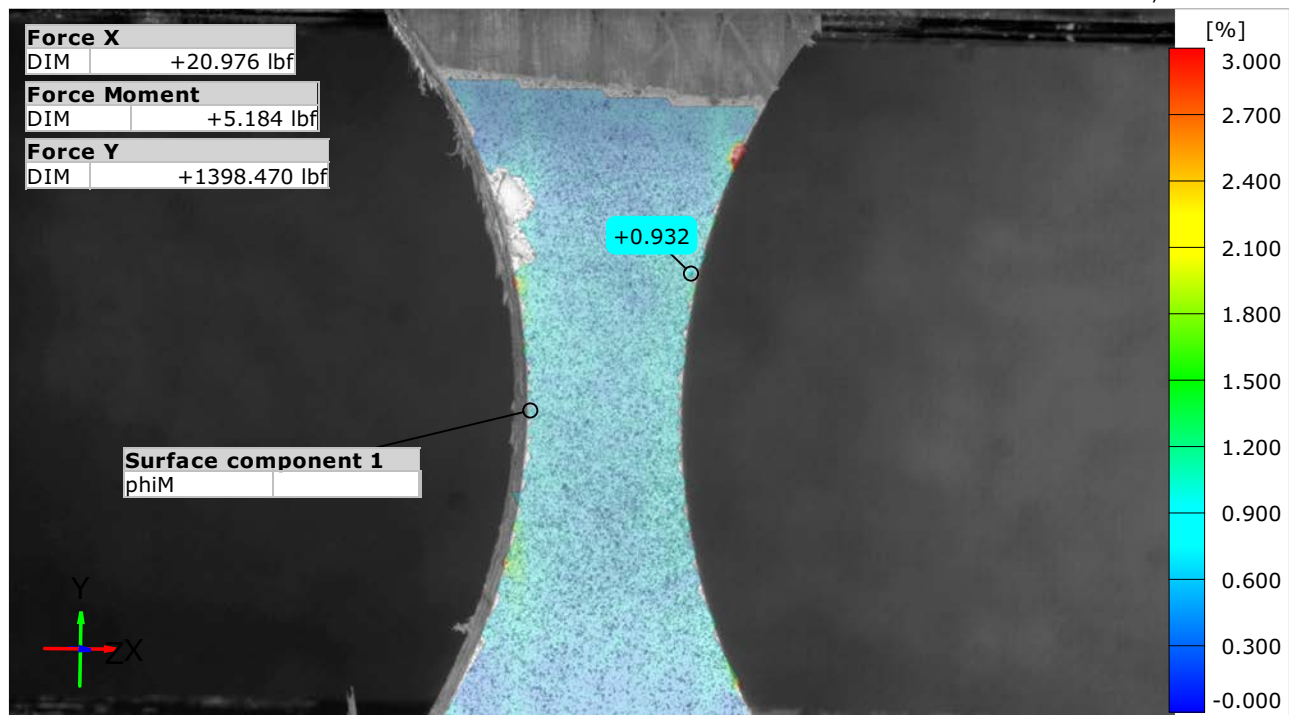
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Uniaxial T5 Failure Example (Sample 134)

79

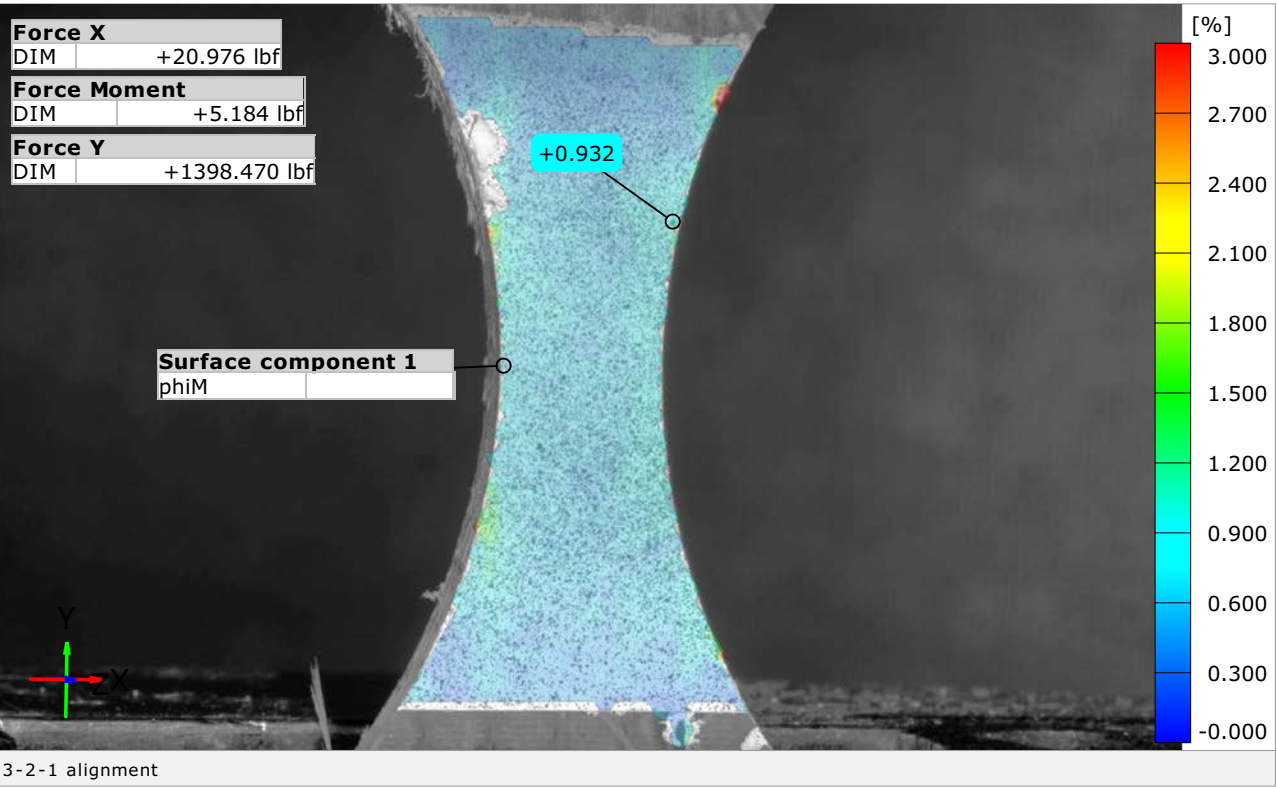
Geometry reference: 1



Uniaxial T5 Further Failure Example (Sample 134)

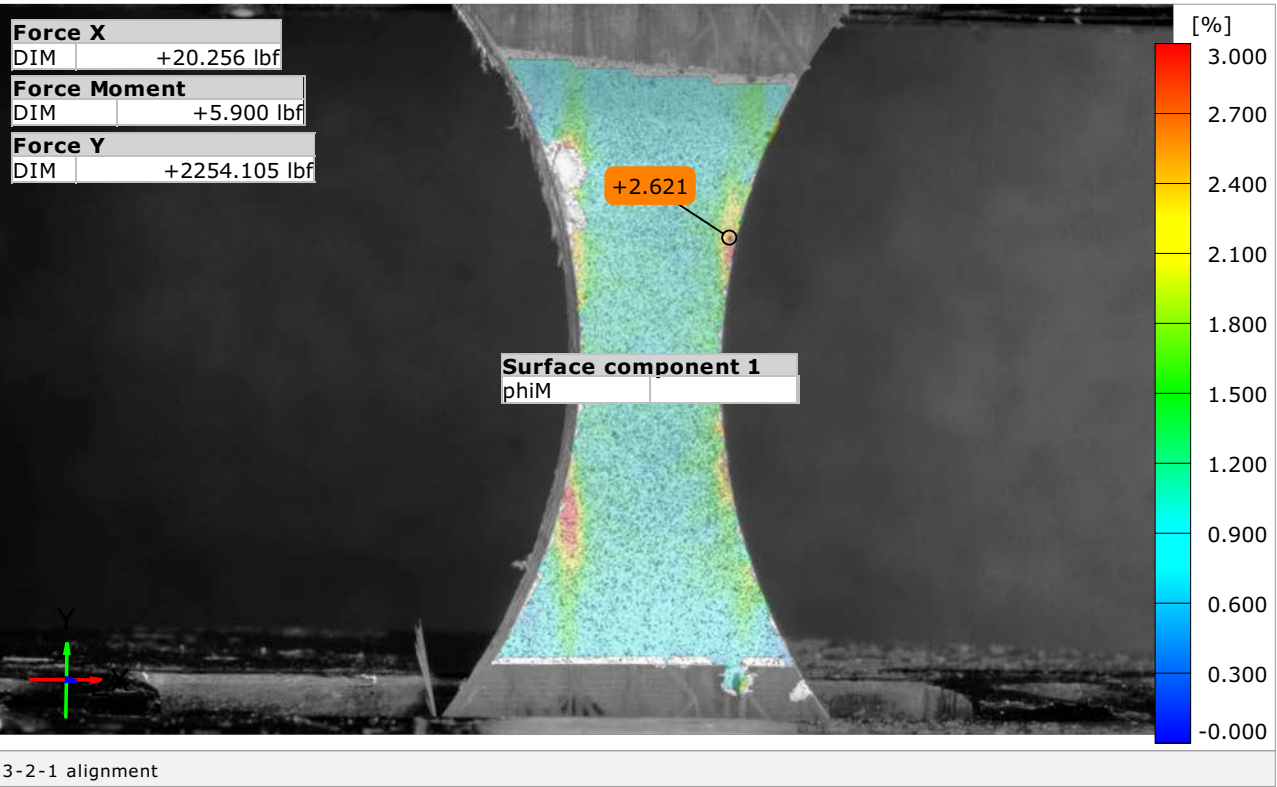
79

Geometry reference: 1



125

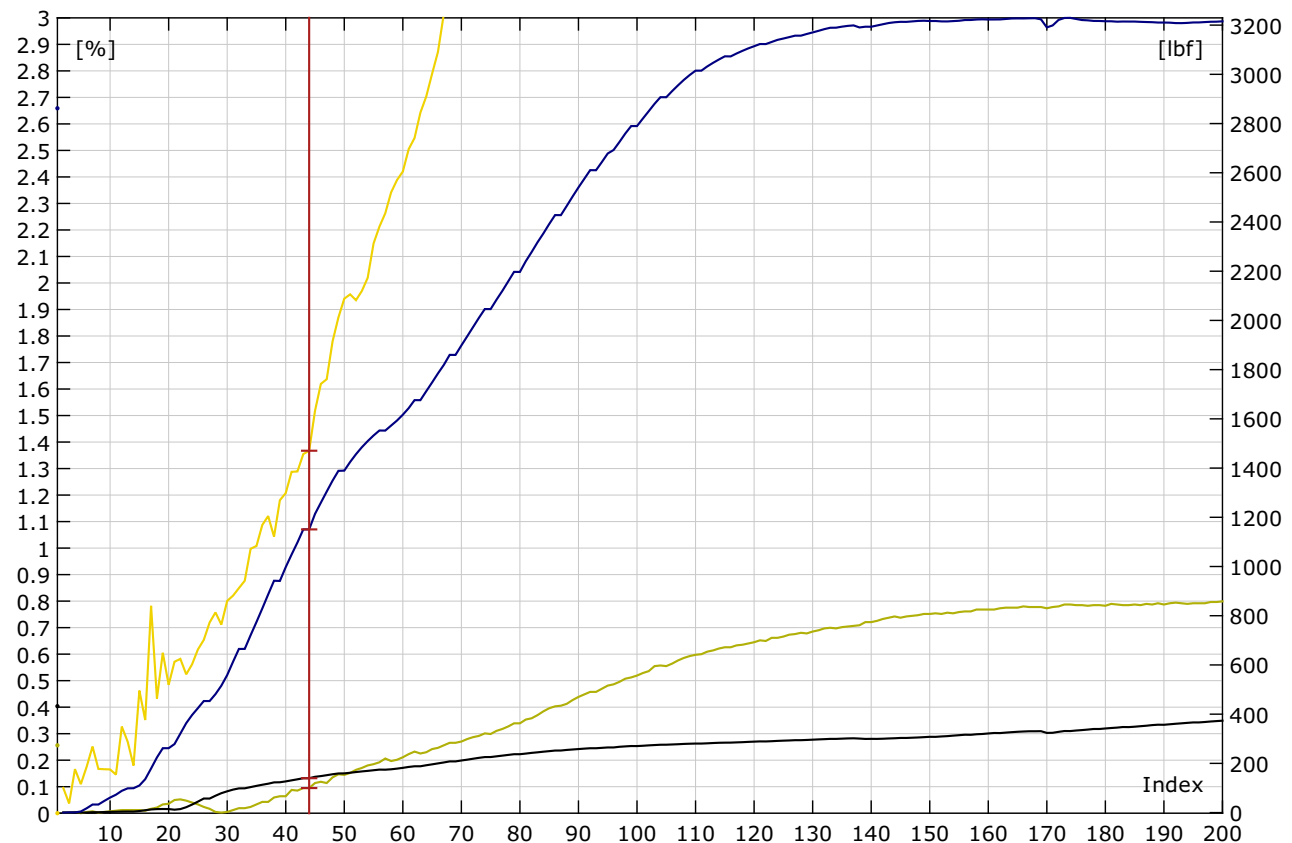
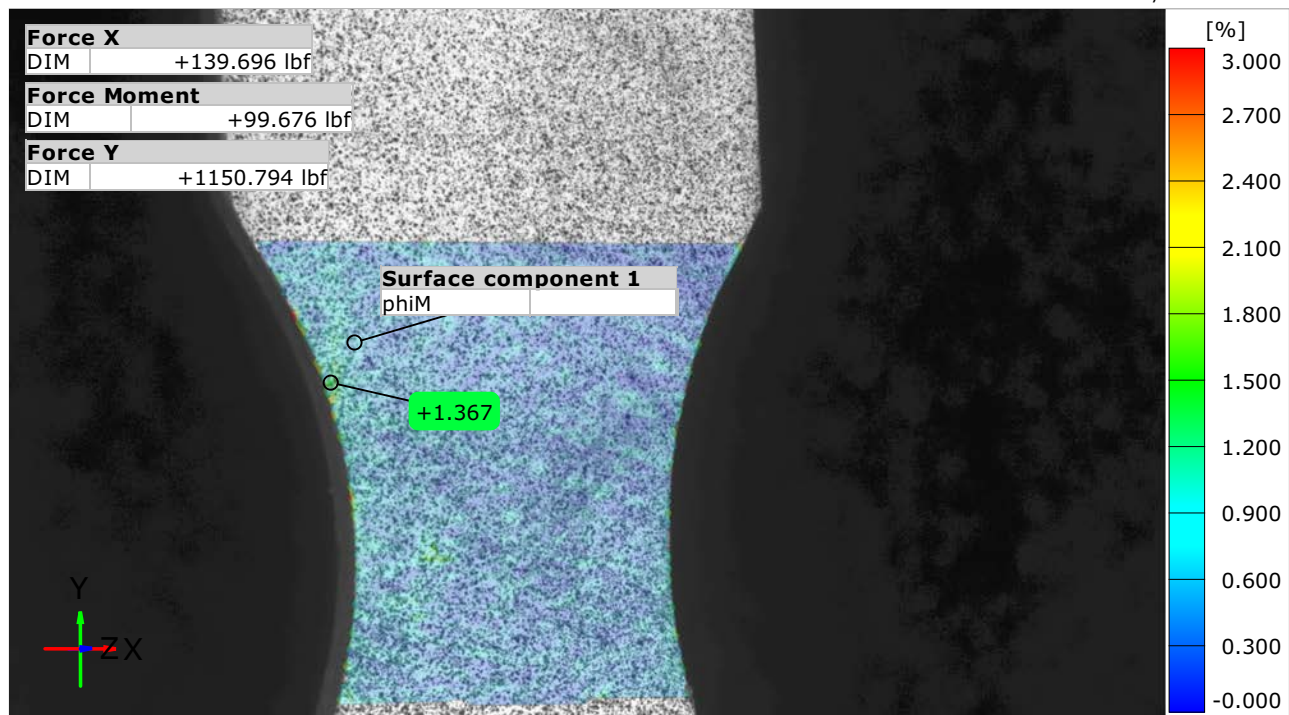
Geometry reference: 1



Uniaxial T6 Failure Example (Sample 153)

44

Geometry reference: 1



3-2-1 alignment

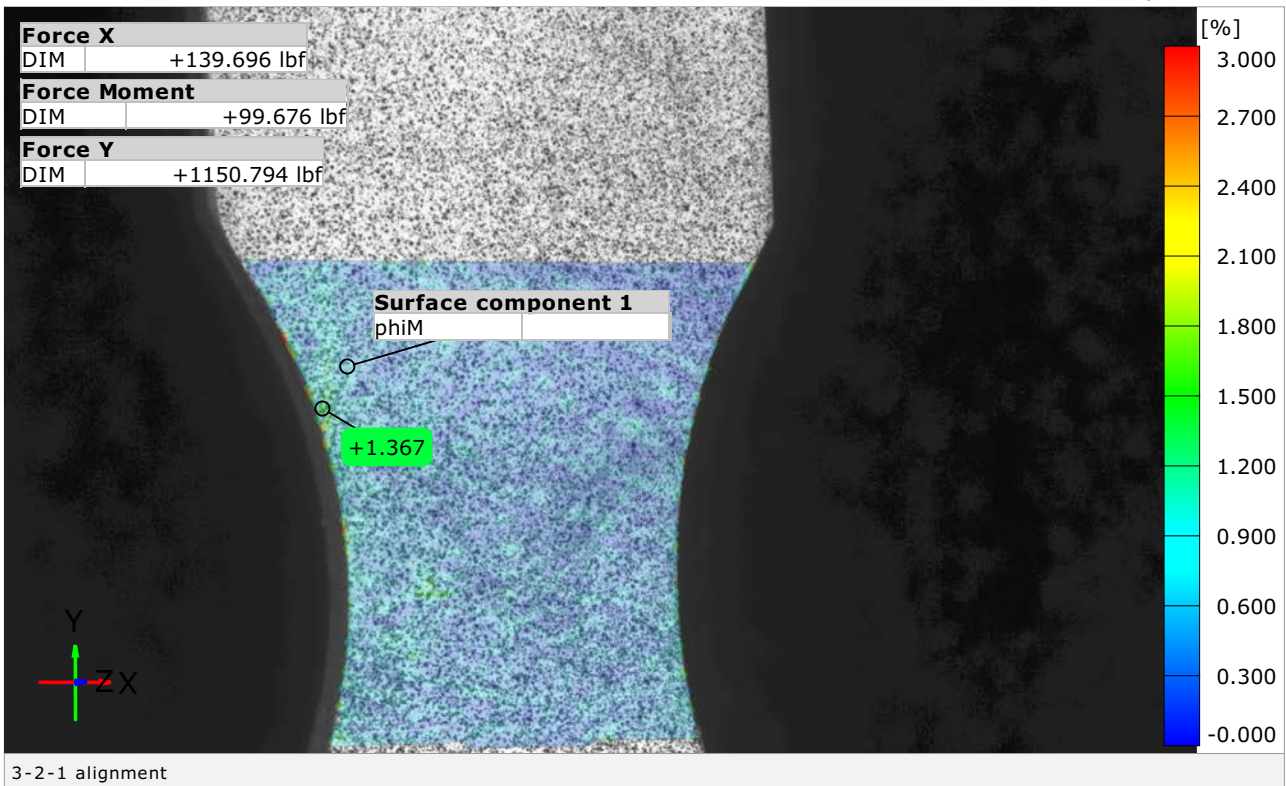
12.07.2024

1/2

Uniaxial T6 Further Failure Example (Sample 153)

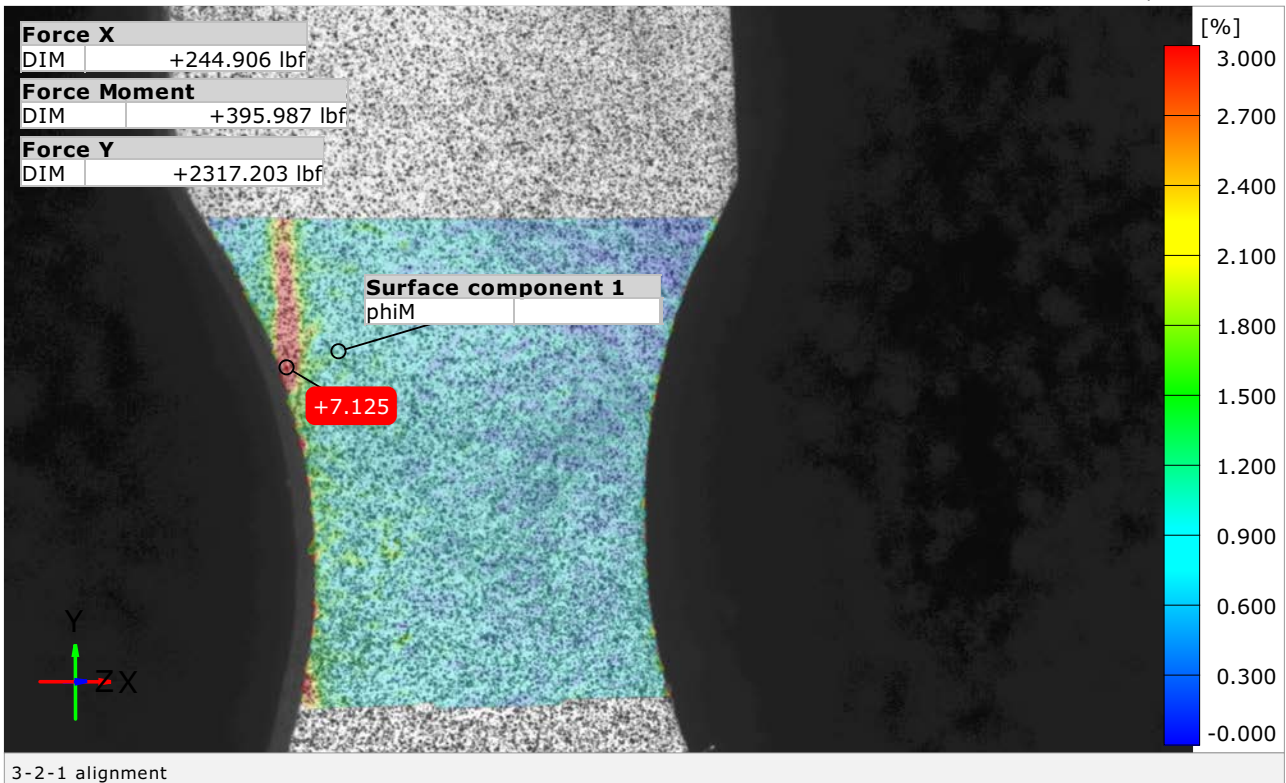
44

Geometry reference: 1



83

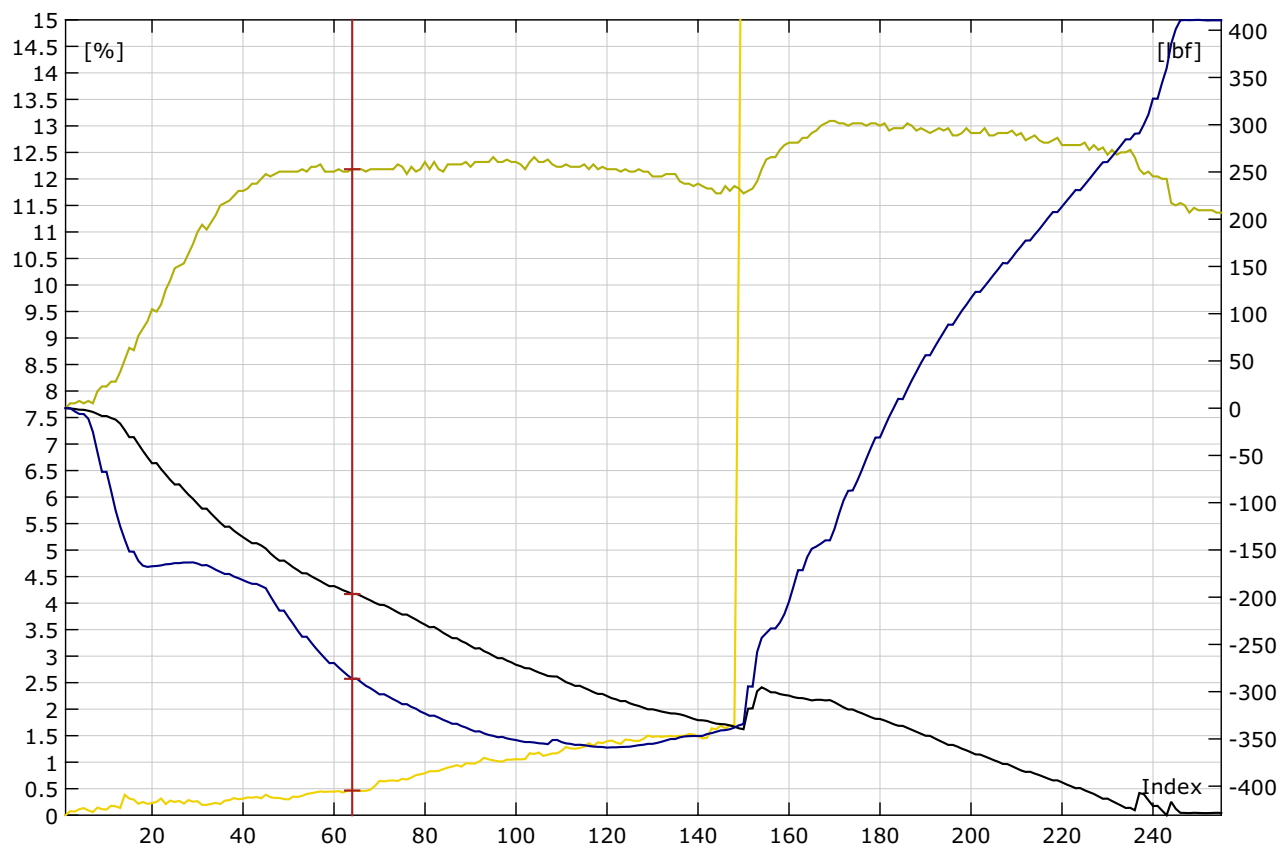
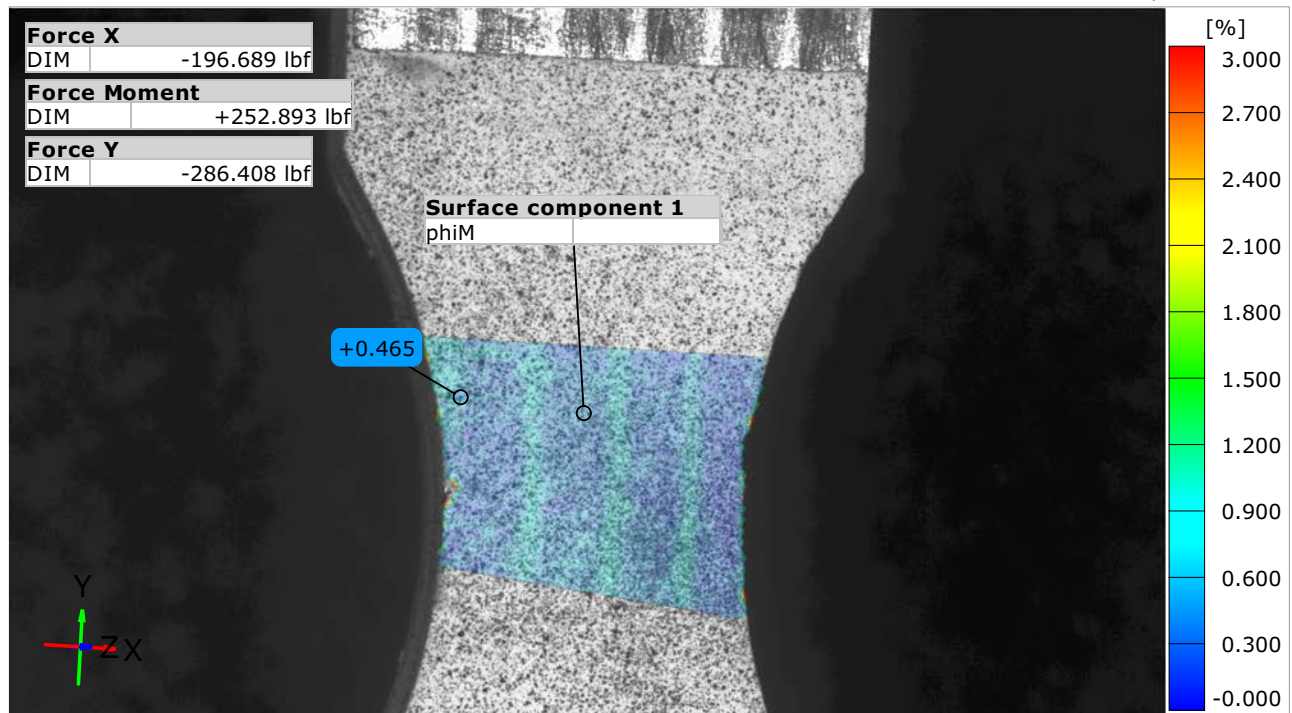
Geometry reference: 1



Uniaxial T8 Failure Example (Sample 144)

64

Geometry reference: 1



3-2-1 alignment

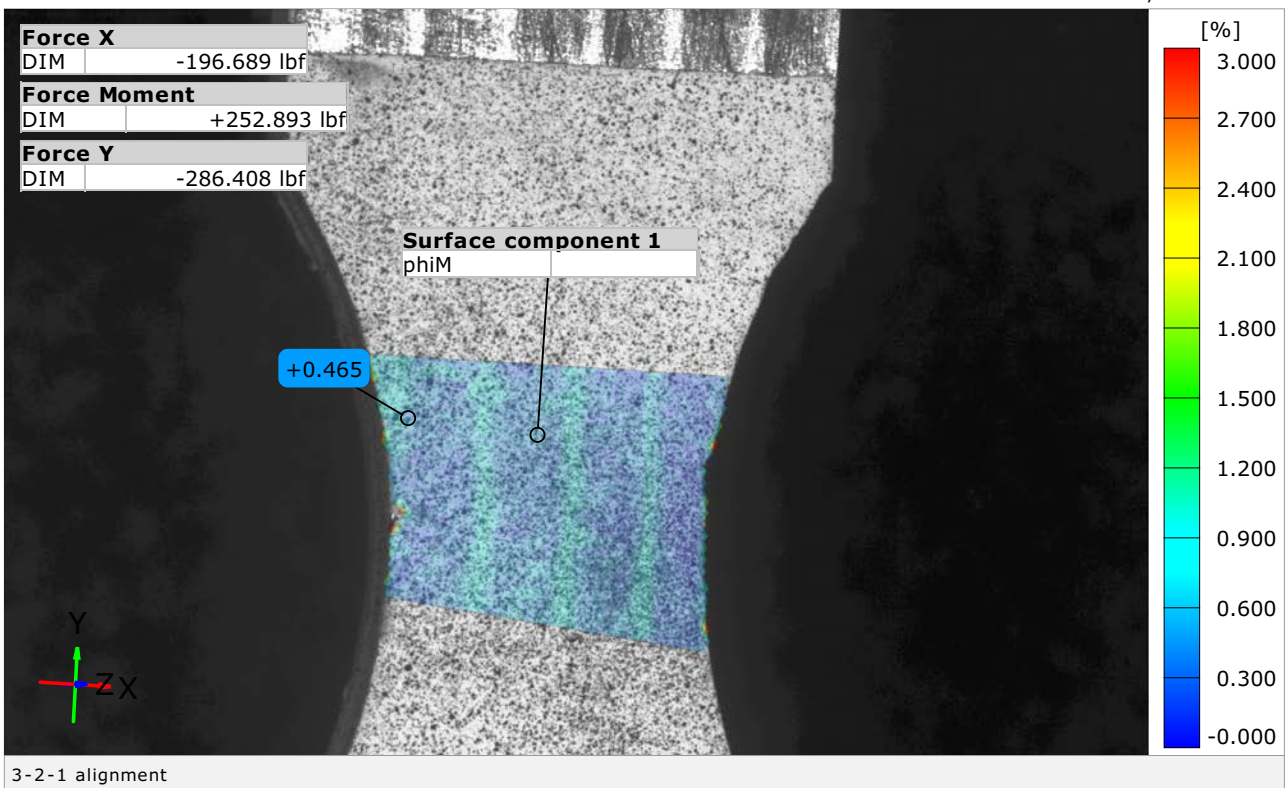
11.07.2024

3/4

Uniaxial T8 Further Failure Example (Sample 144)

64

Geometry reference: 1



150

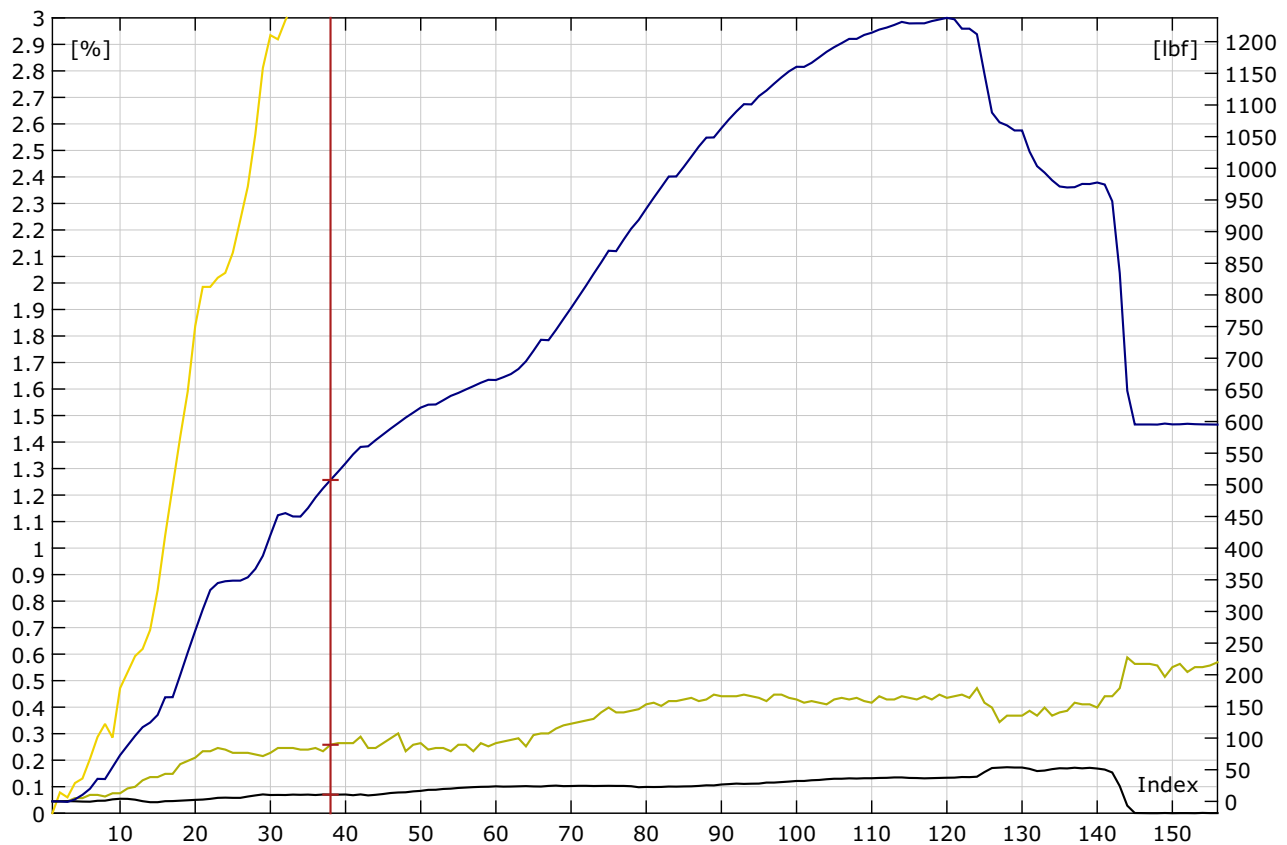
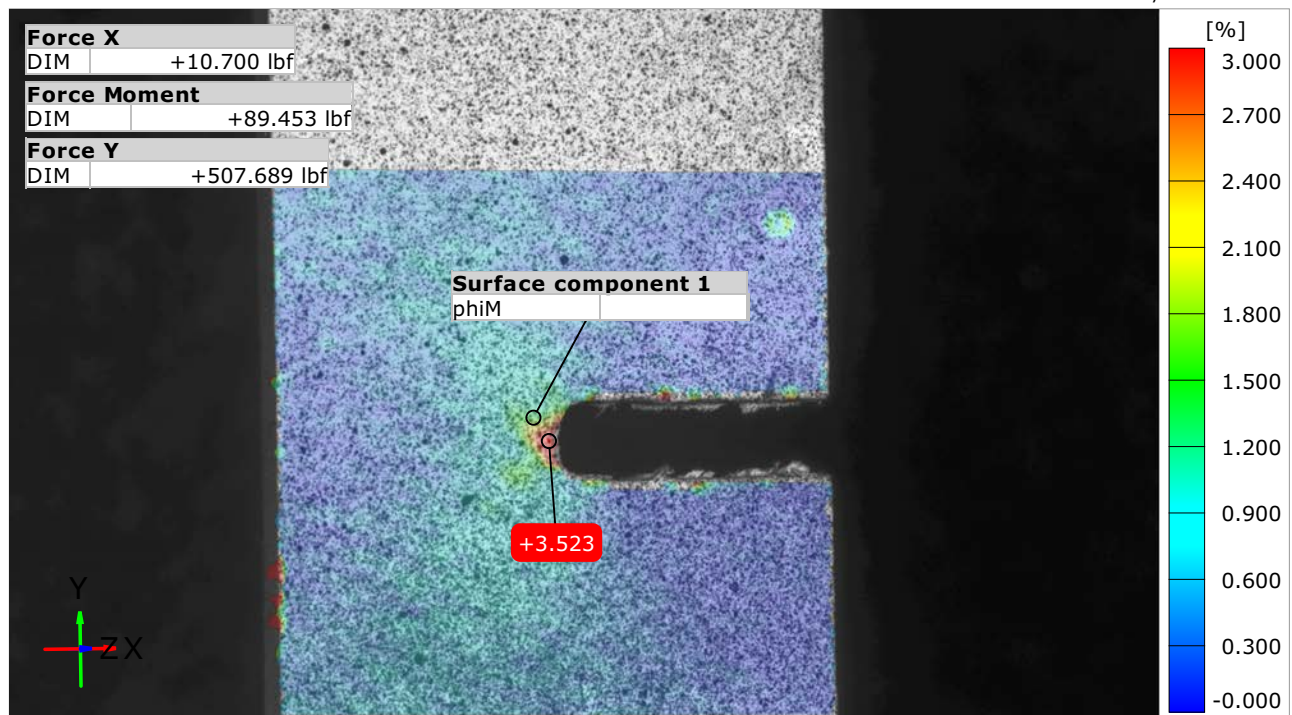
Geometry reference: 1



Biaxial T1 Failure Example (Sample 224)

38

Geometry reference: 1



3-2-1 alignment

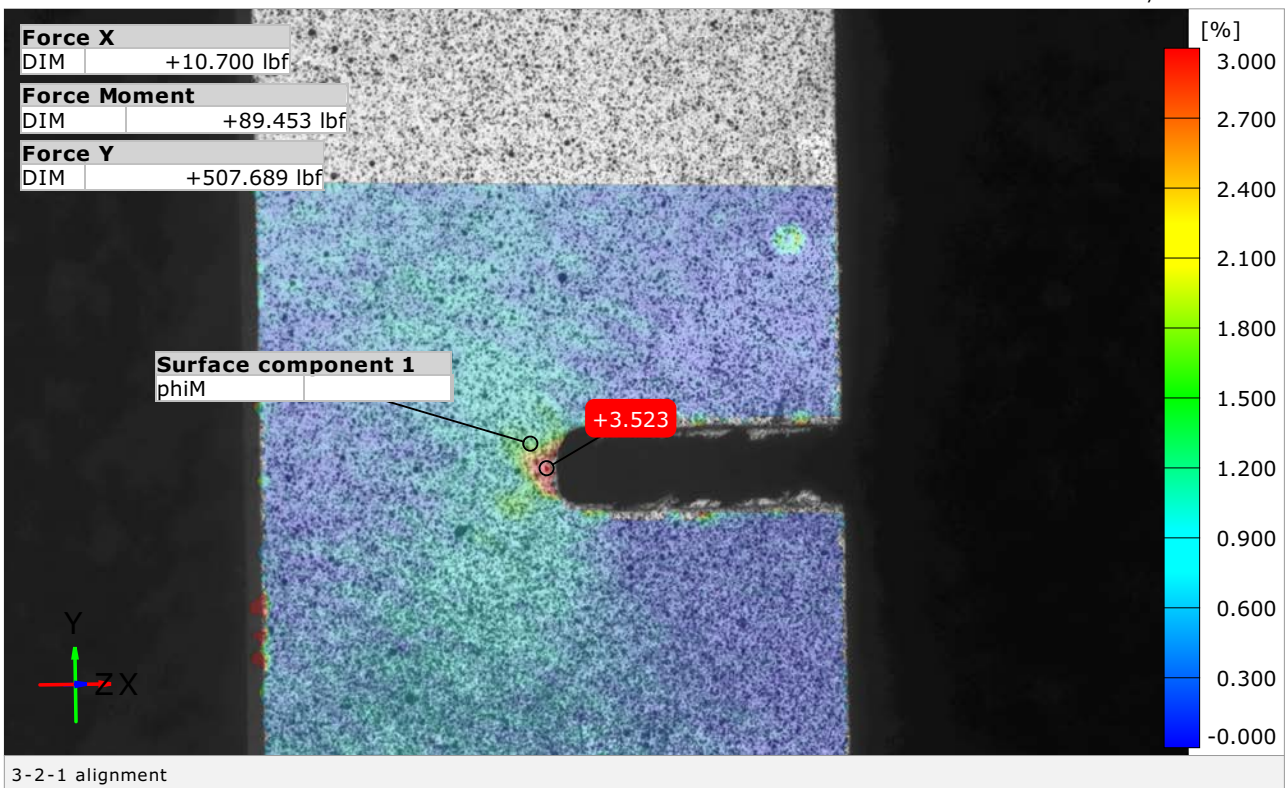
15.07.2024

3/4

Biaxial T1 Further Failure Example (Sample 224)

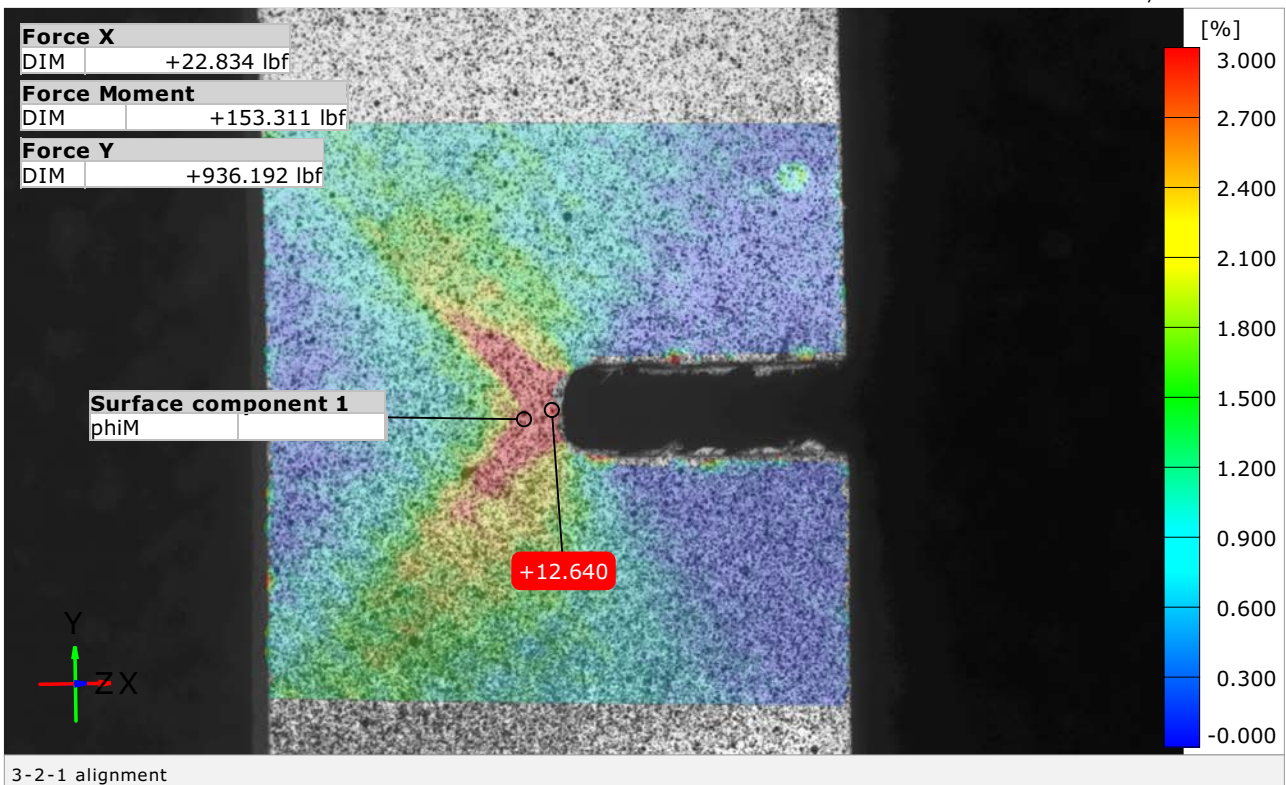
38

Geometry reference: 1



80

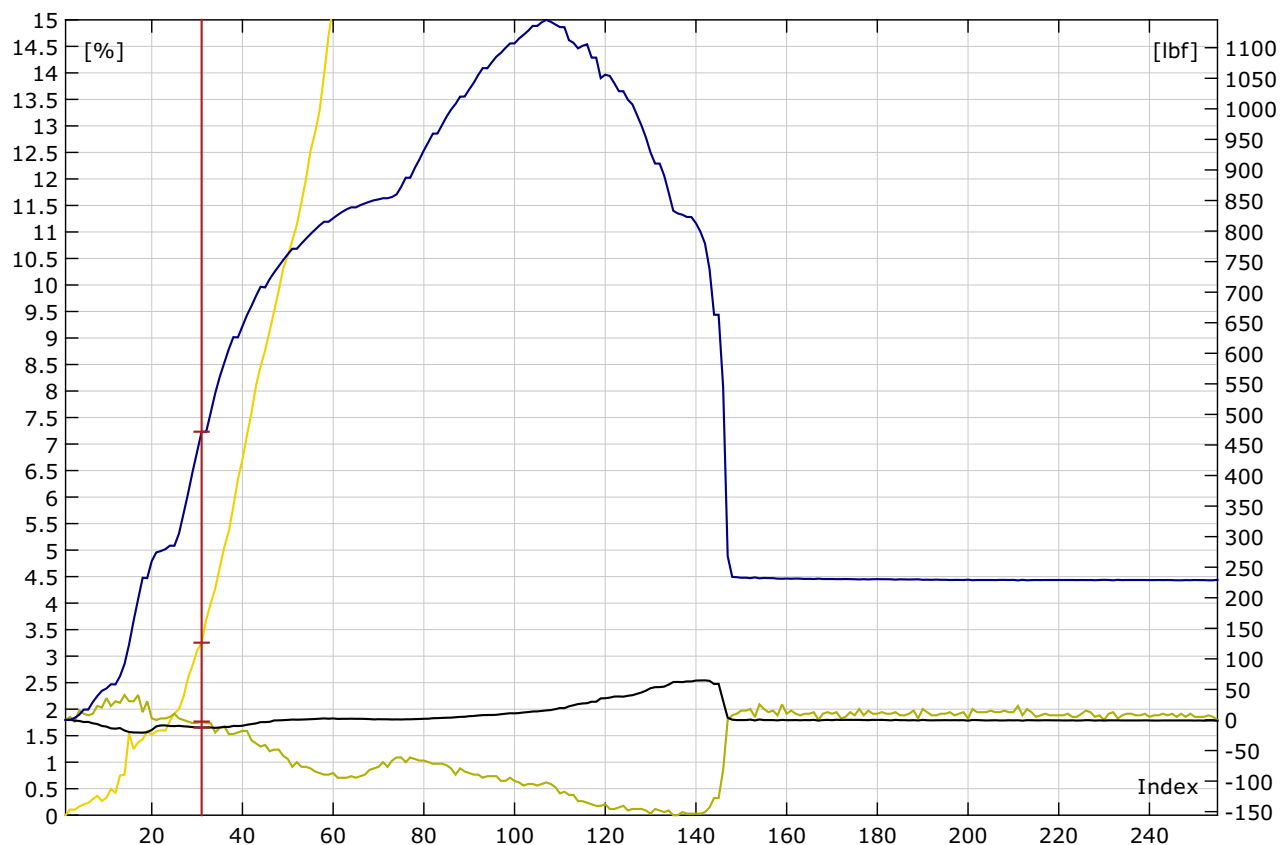
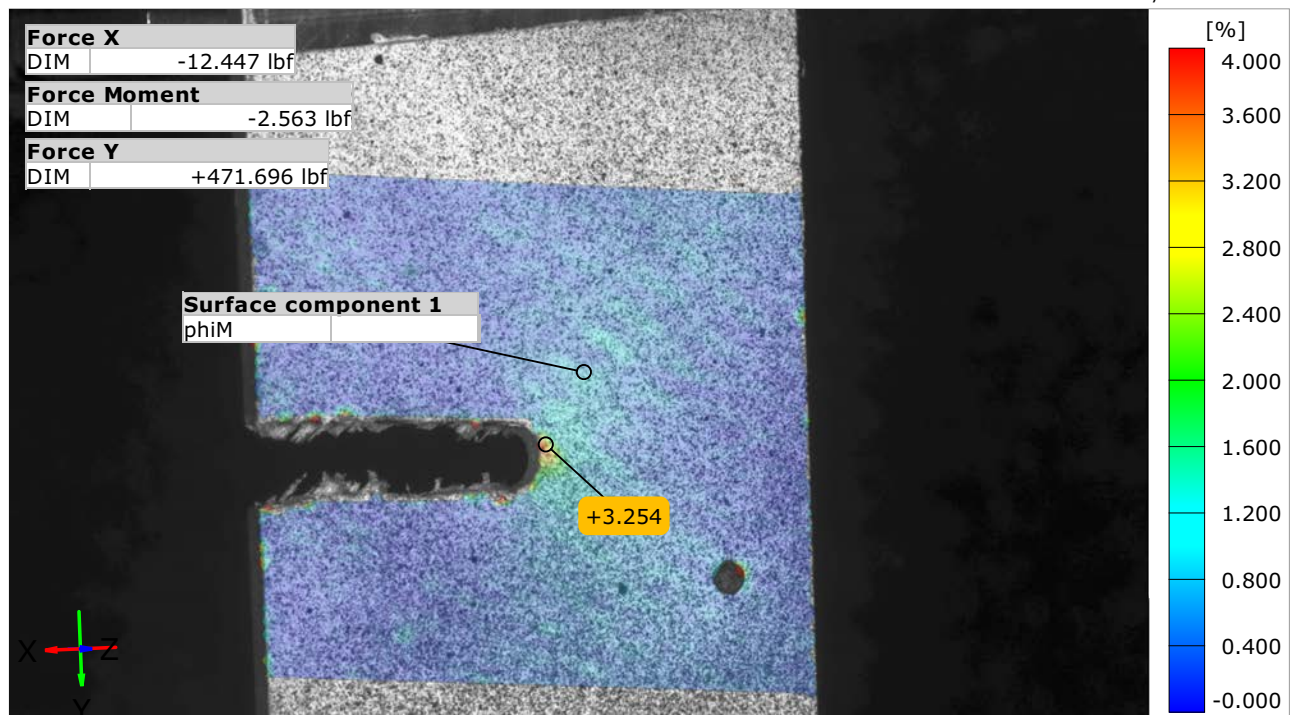
Geometry reference: 1



Biaxial T2 Failure Example (Sample 222)

31

Geometry reference: 1



3-2-1 alignment

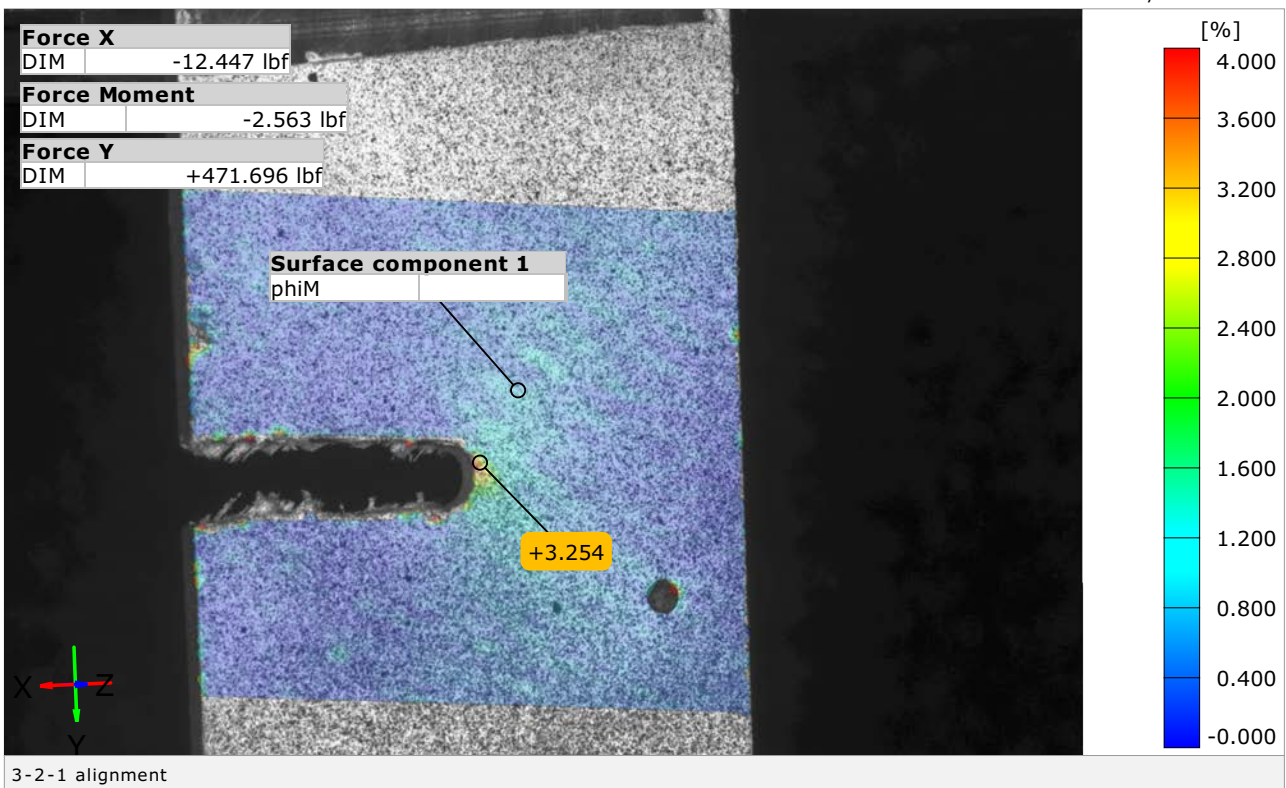
15.07.2024

1/2

Biaxial T2 Further Failure Example (Sample 222)

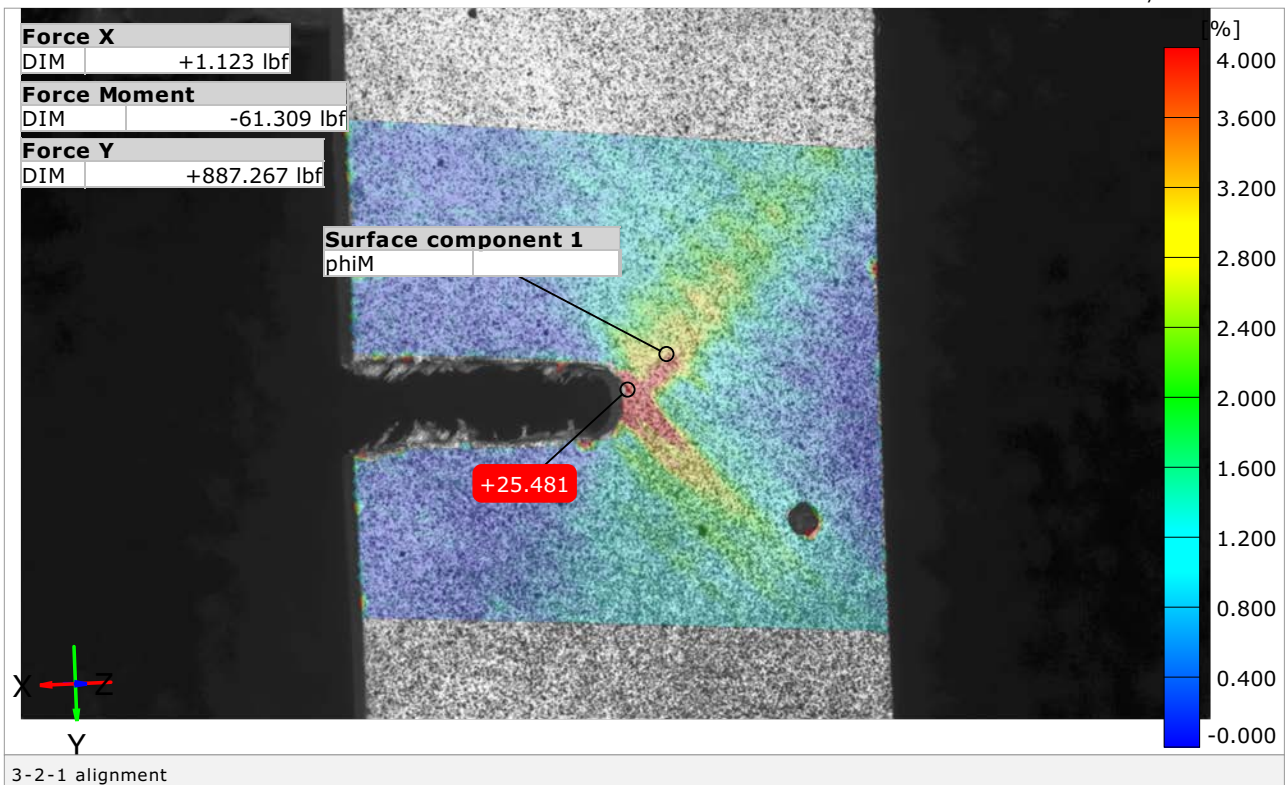
31

Geometry reference: 1



77

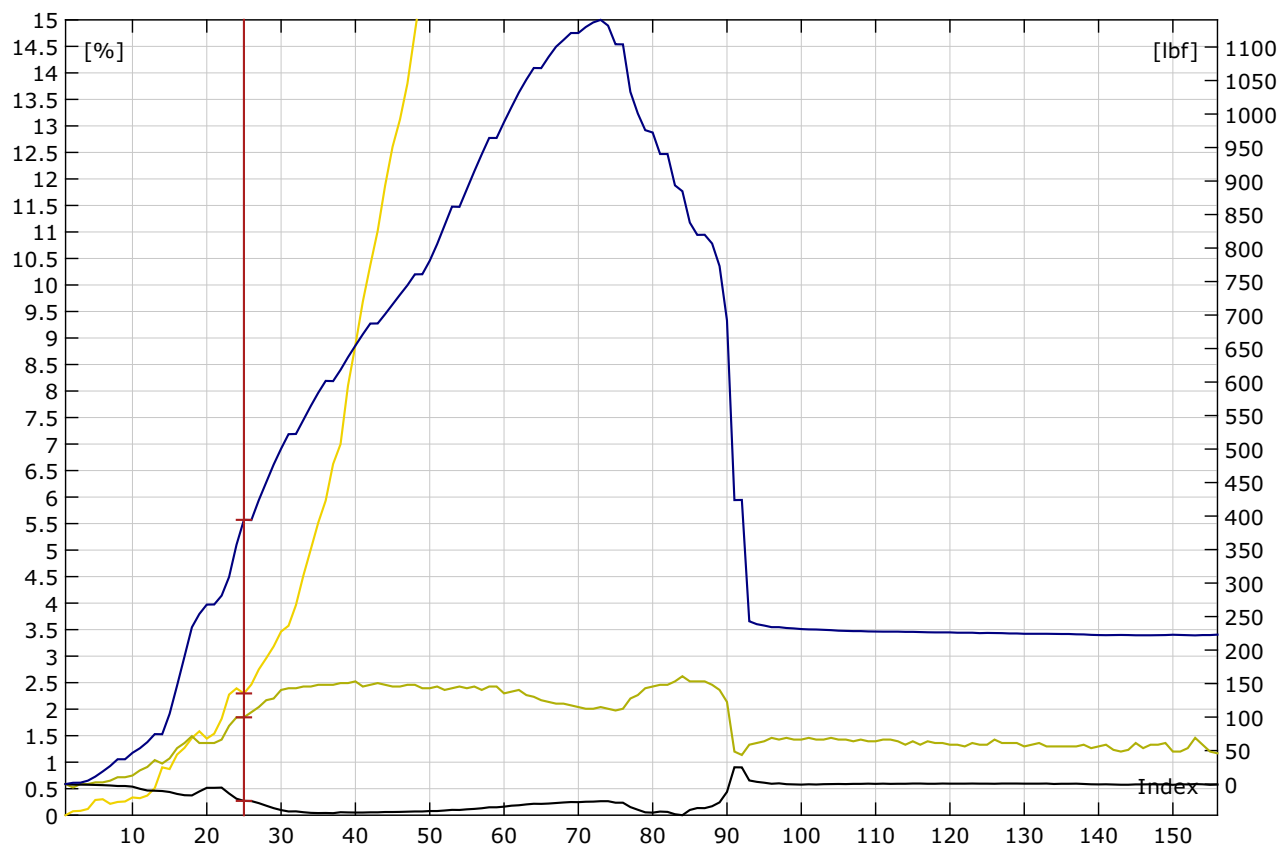
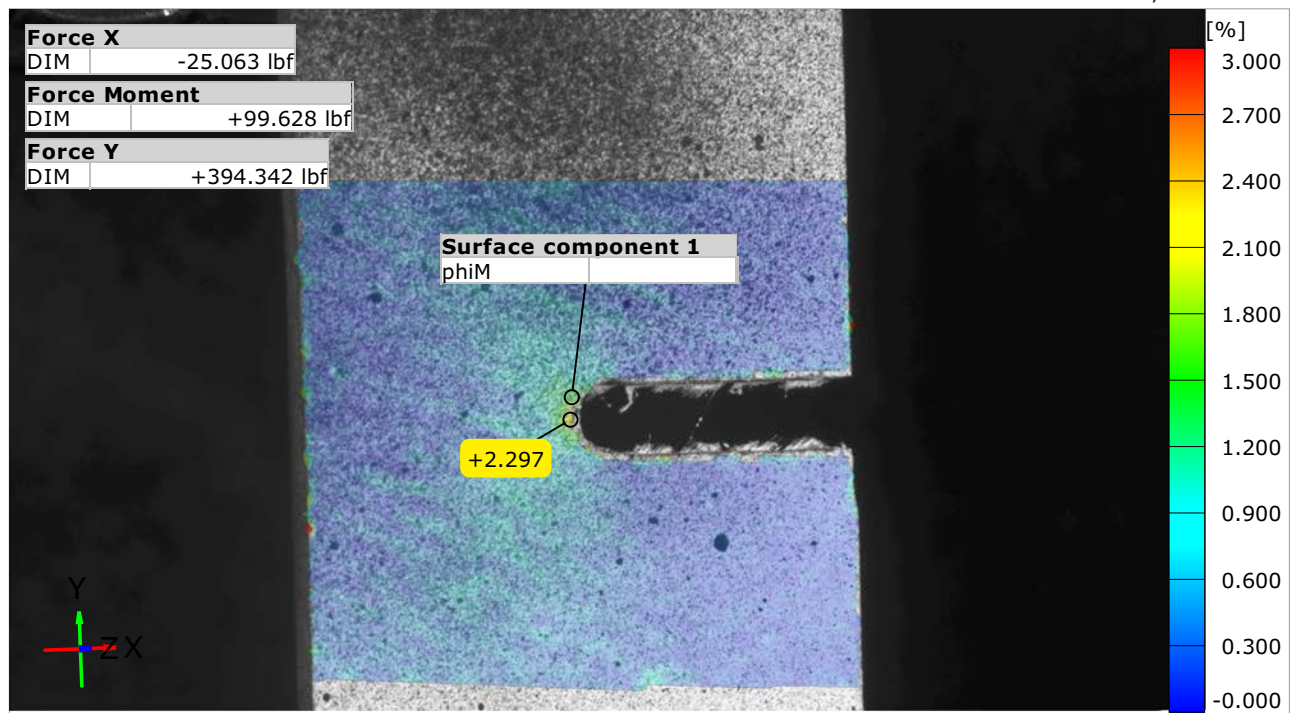
Geometry reference: 1



Biaxial T3 Failure Example (Sample 213)

25

Geometry reference: 1



3-2-1 alignment

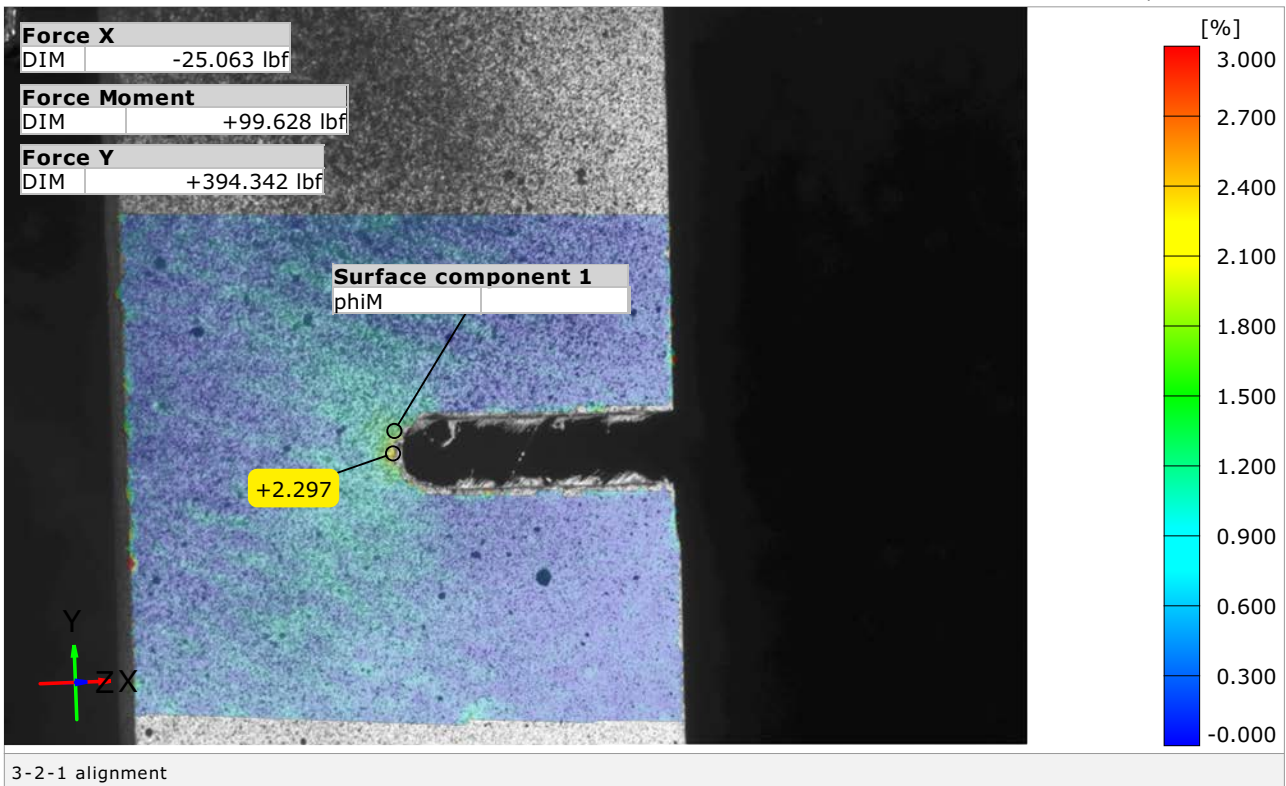
15.07.2024

1/2

Biaxial T3 Further Failure Example (Sample 213)

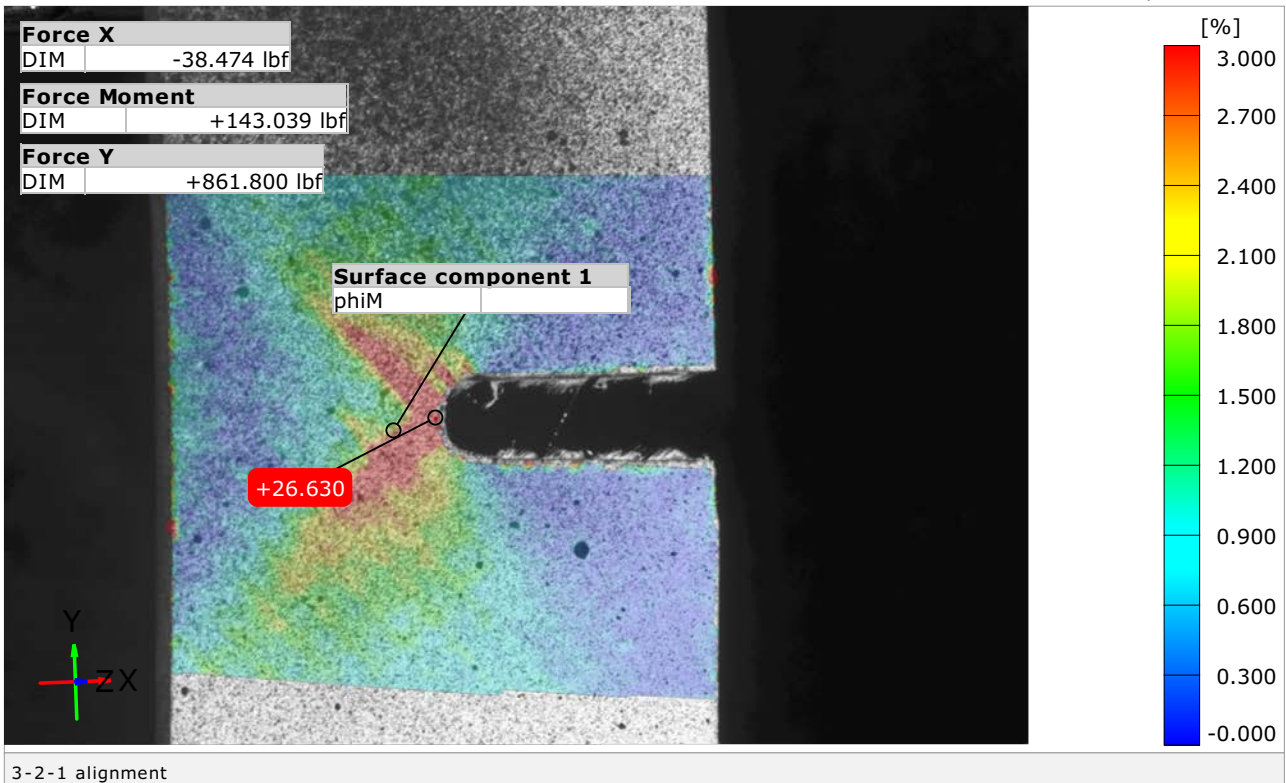
25

Geometry reference: 1



53

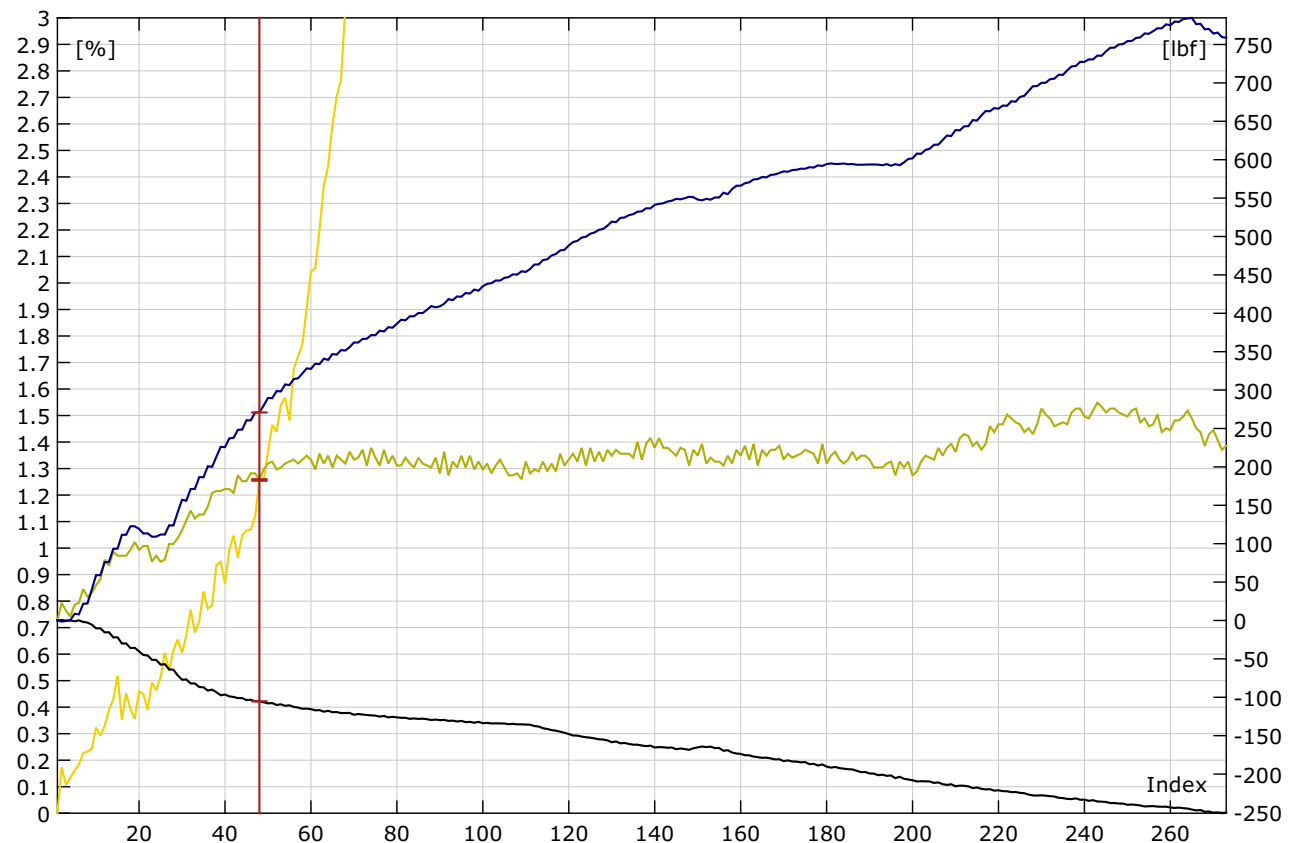
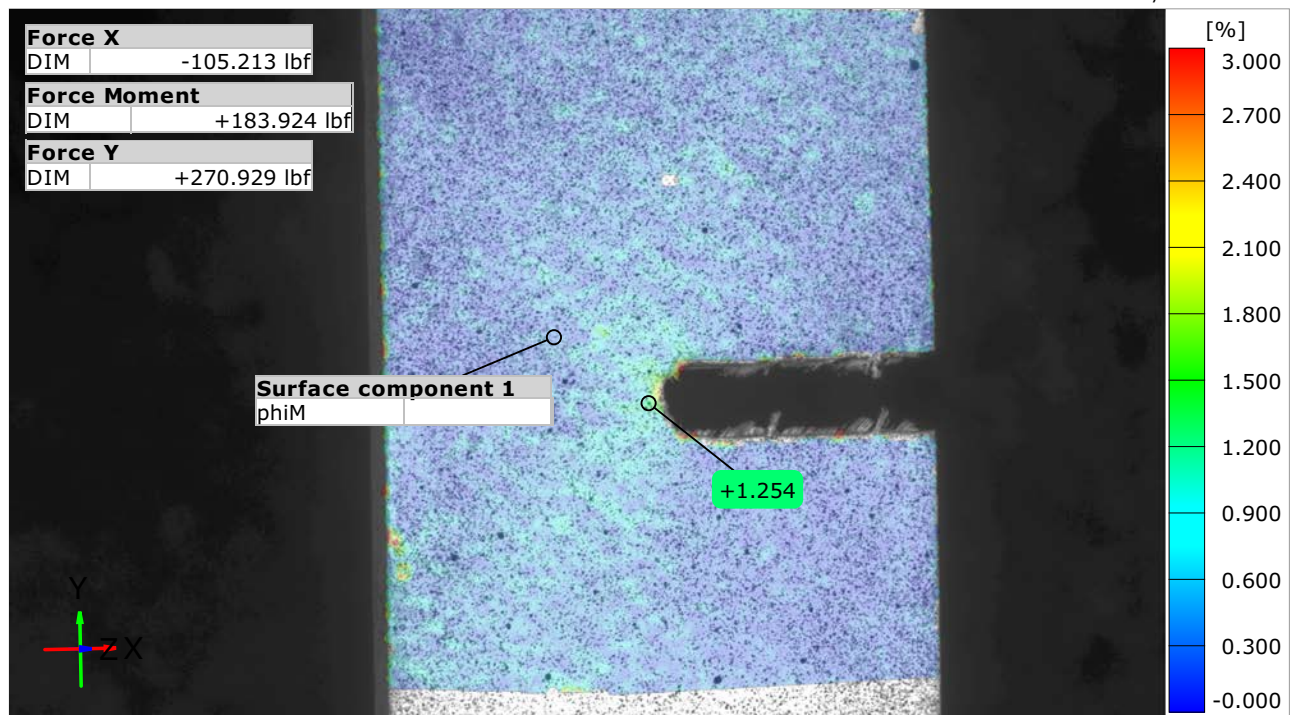
Geometry reference: 1



Biaxial T4 Failure Example (Sample 203)

48

Geometry reference: 1



3-2-1 alignment

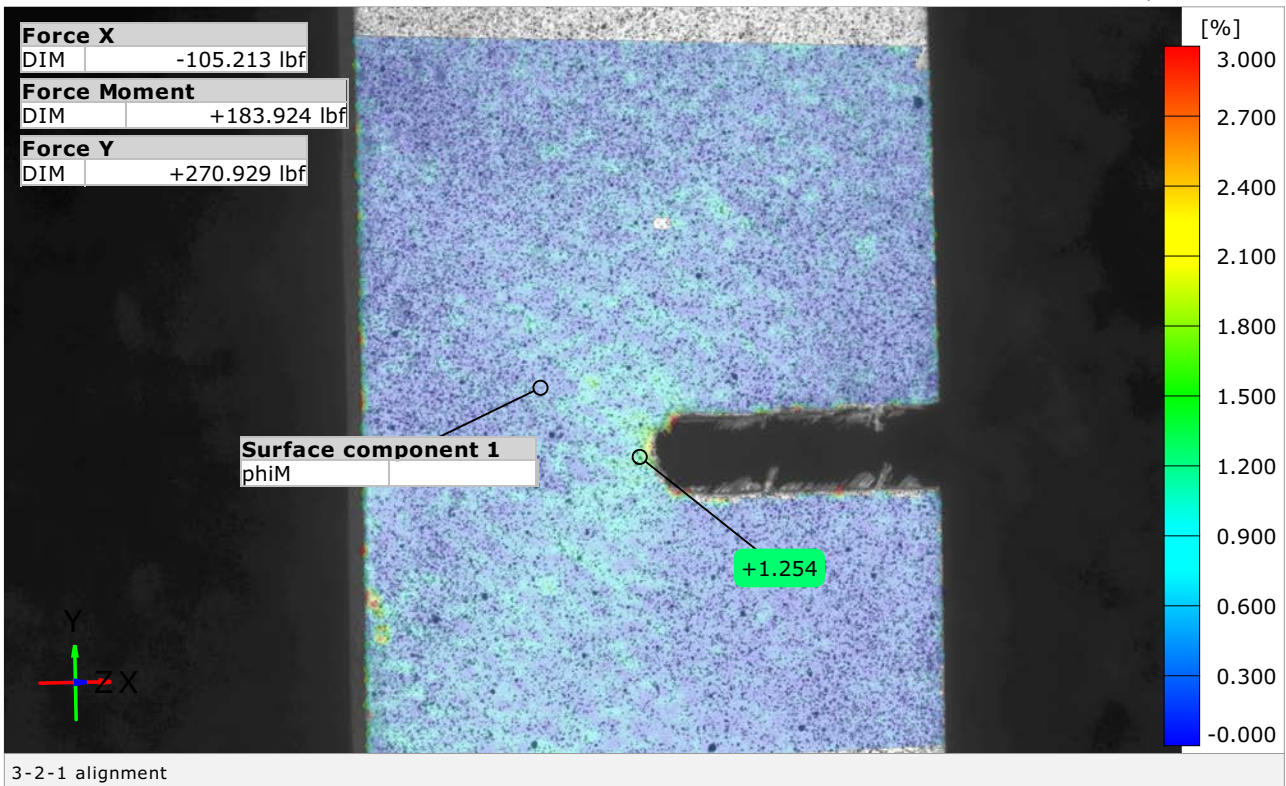
16.07.2024

3/4

Biaxial T4 Further Failure Example (Sample 203)

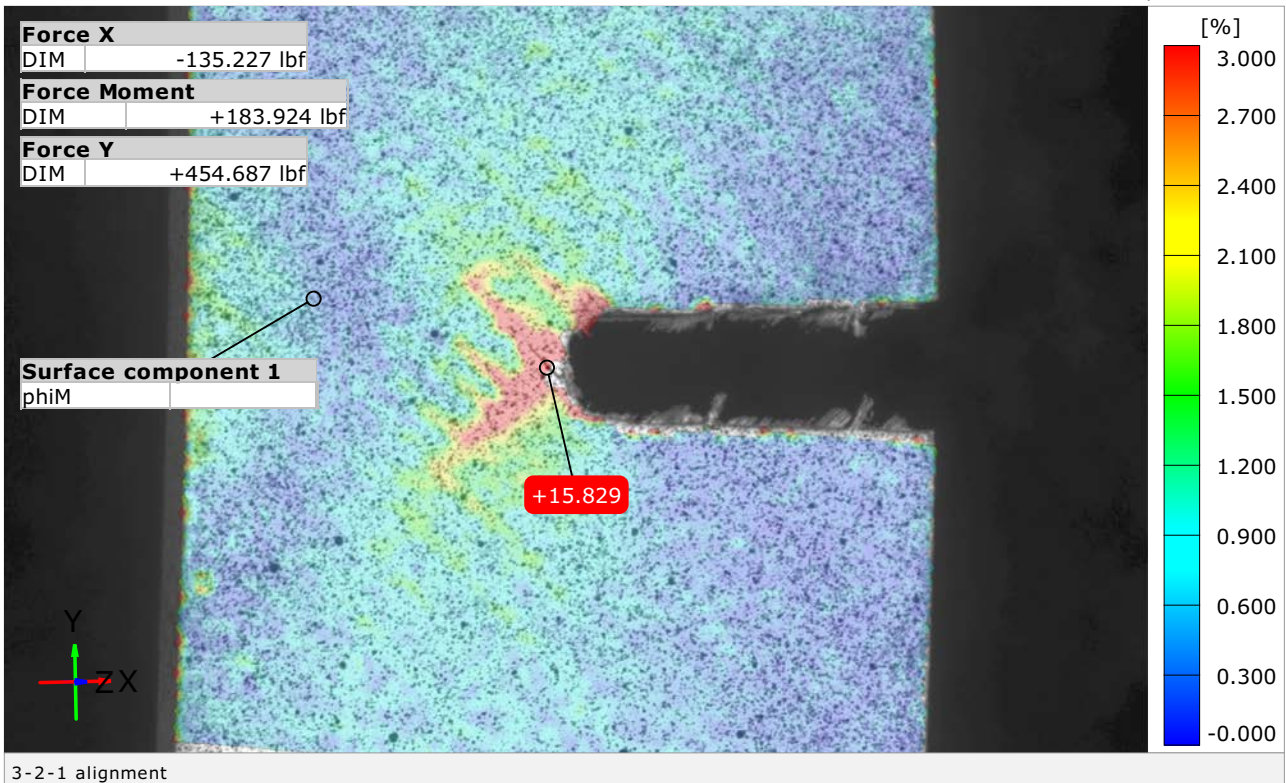
48

Geometry reference: 1



109

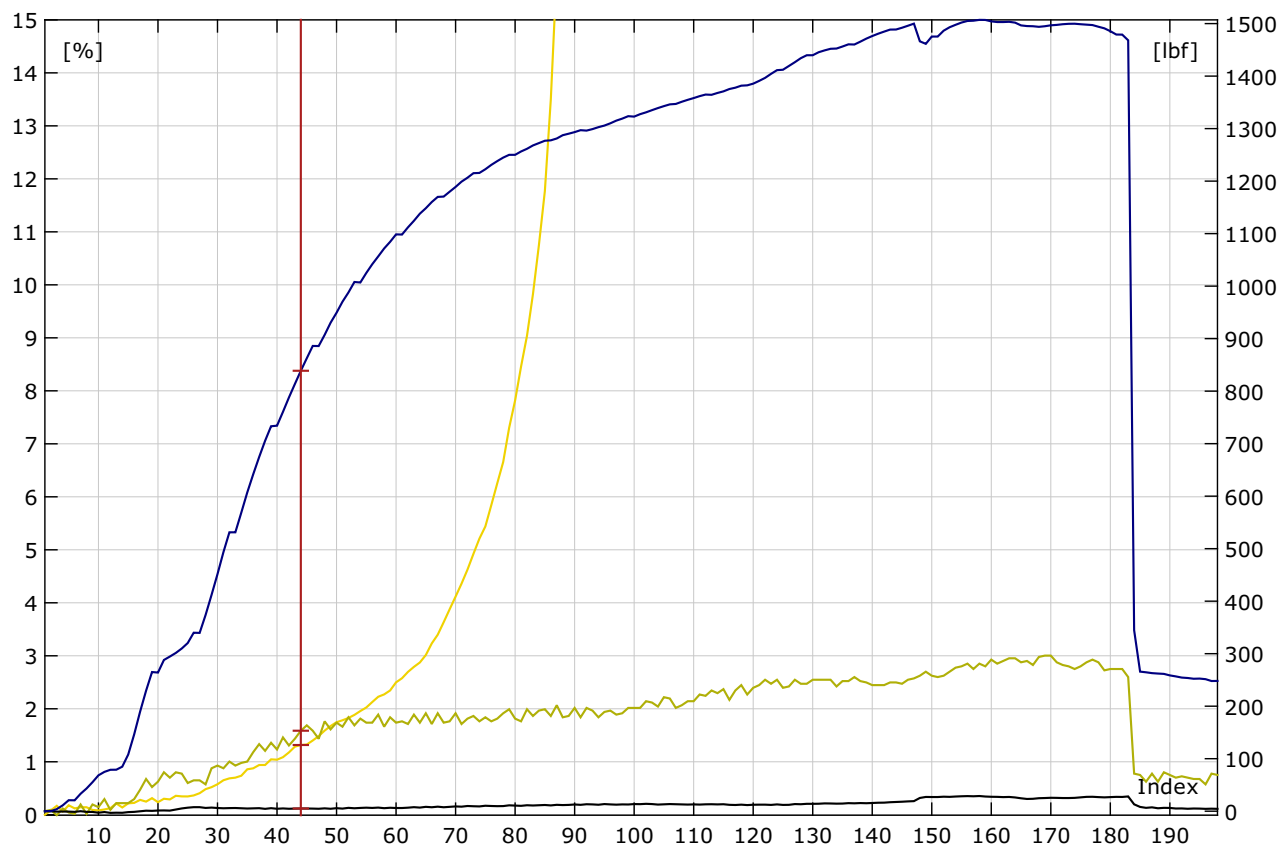
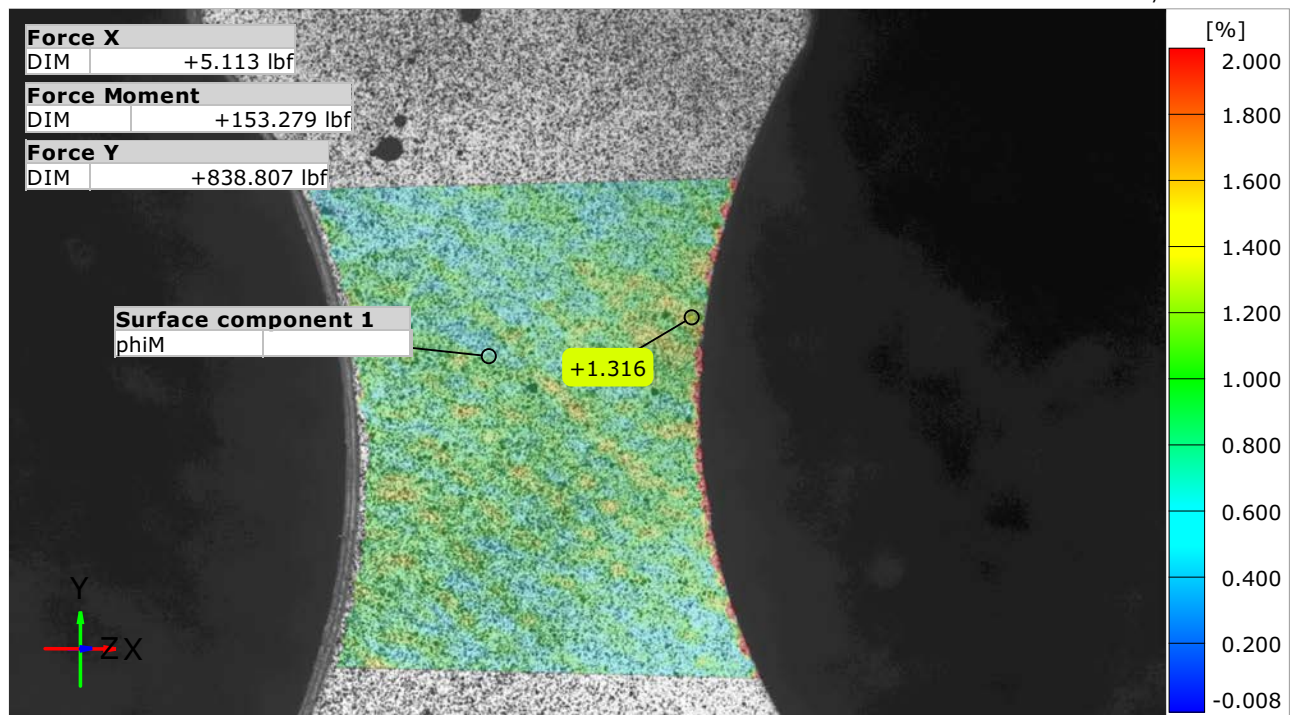
Geometry reference: 1



Biaxial T5 Failure Example (Sample 247)

44

Geometry reference: 1



3-2-1 alignment

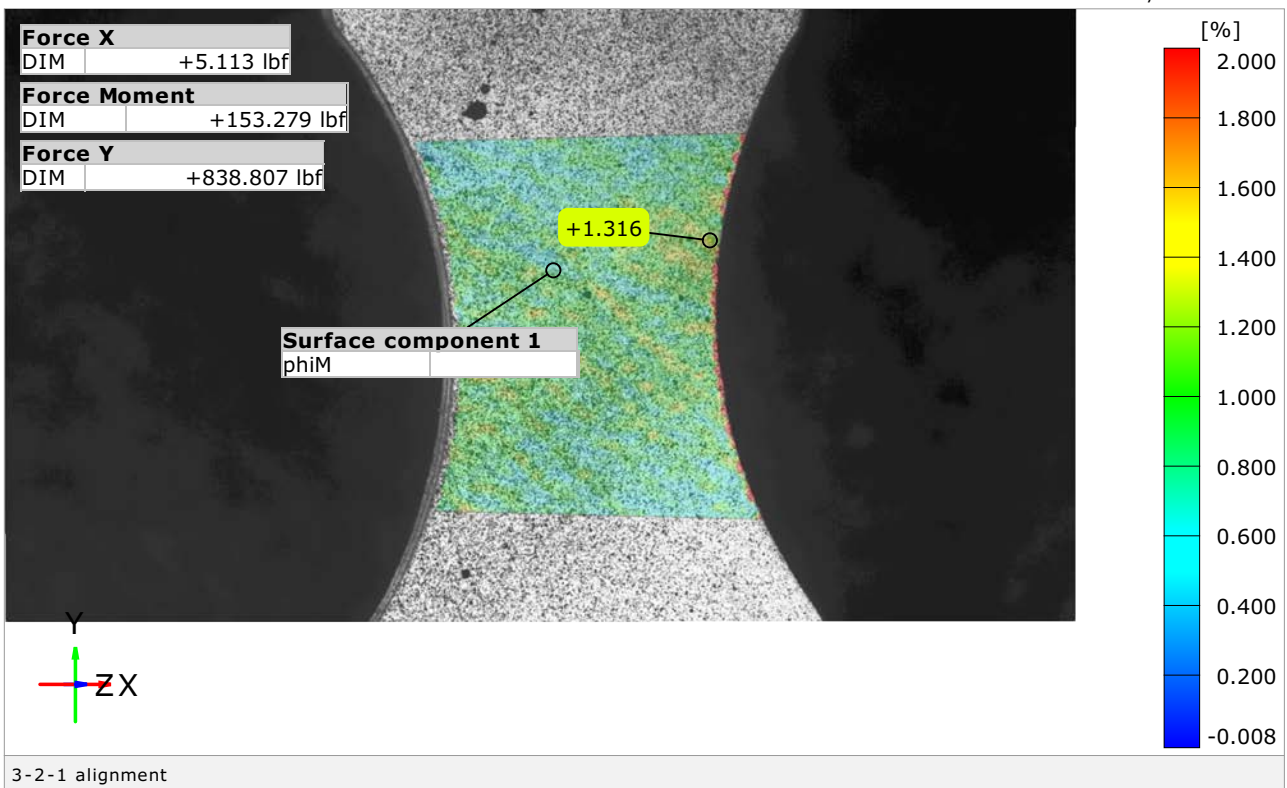
16.07.2024

1/2

Biaxial T5 Further Failure Example (Sample 247)

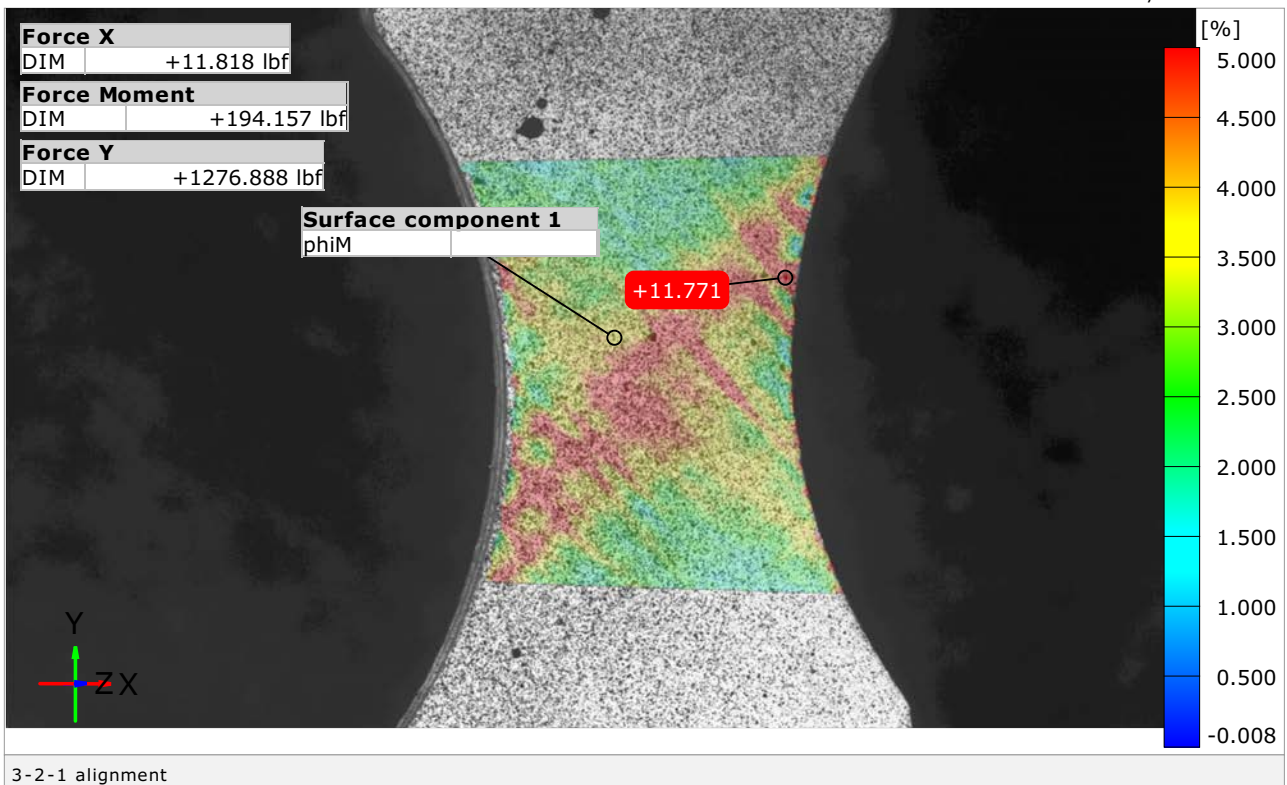
44

Geometry reference: 1



85

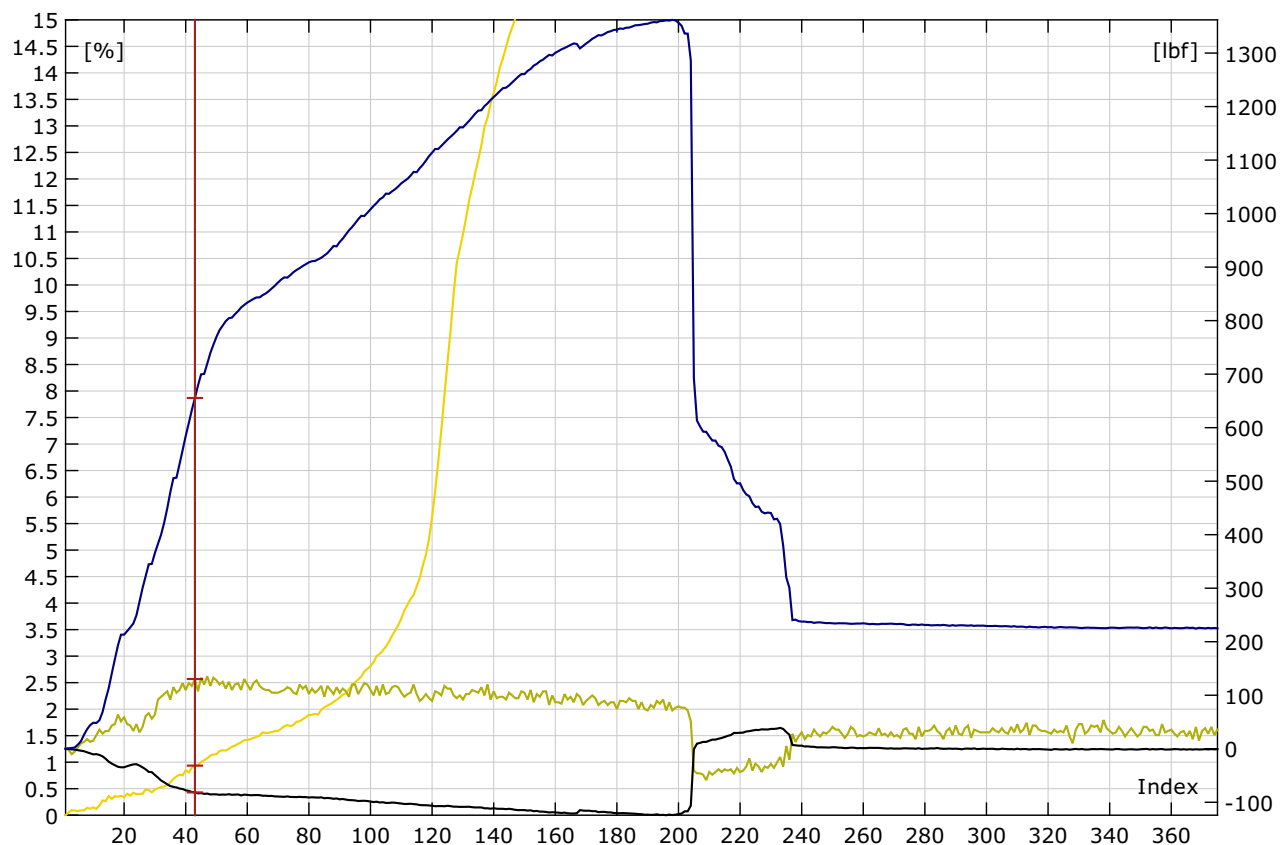
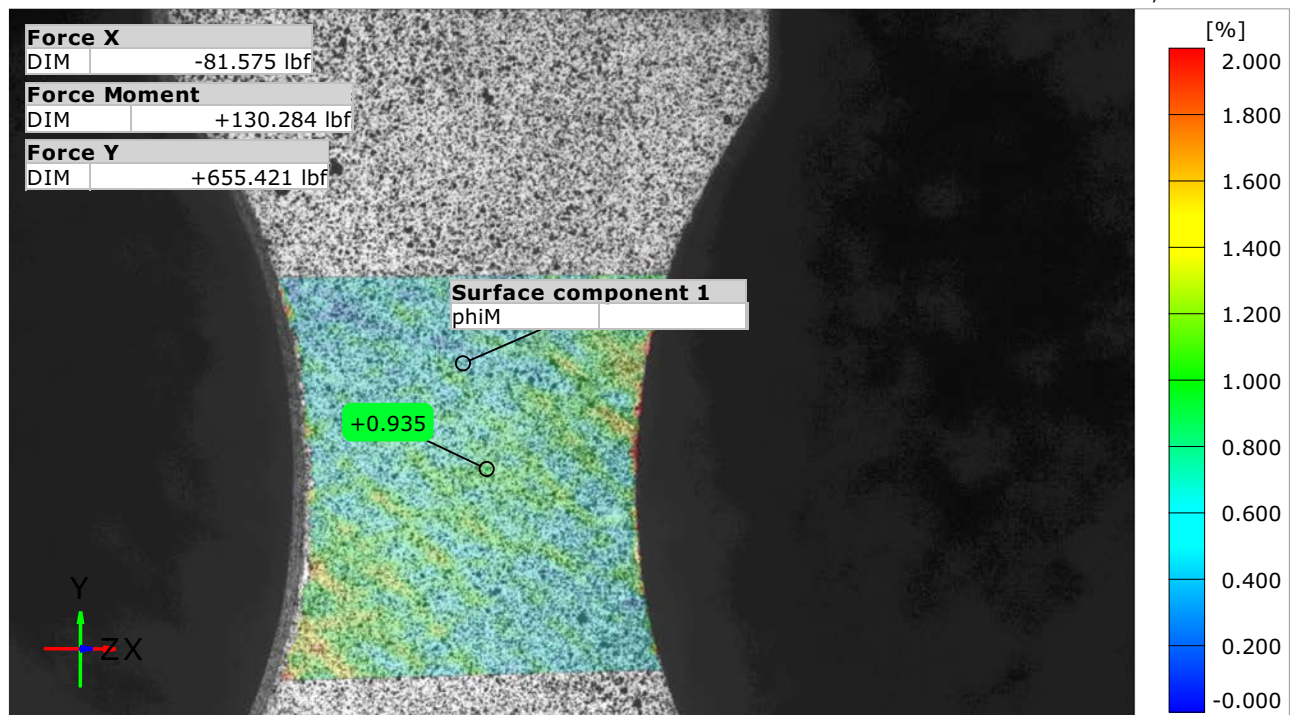
Geometry reference: 1



Biaxial T6 Failure Example (Sample 250)

43

Geometry reference: 1



3-2-1 alignment

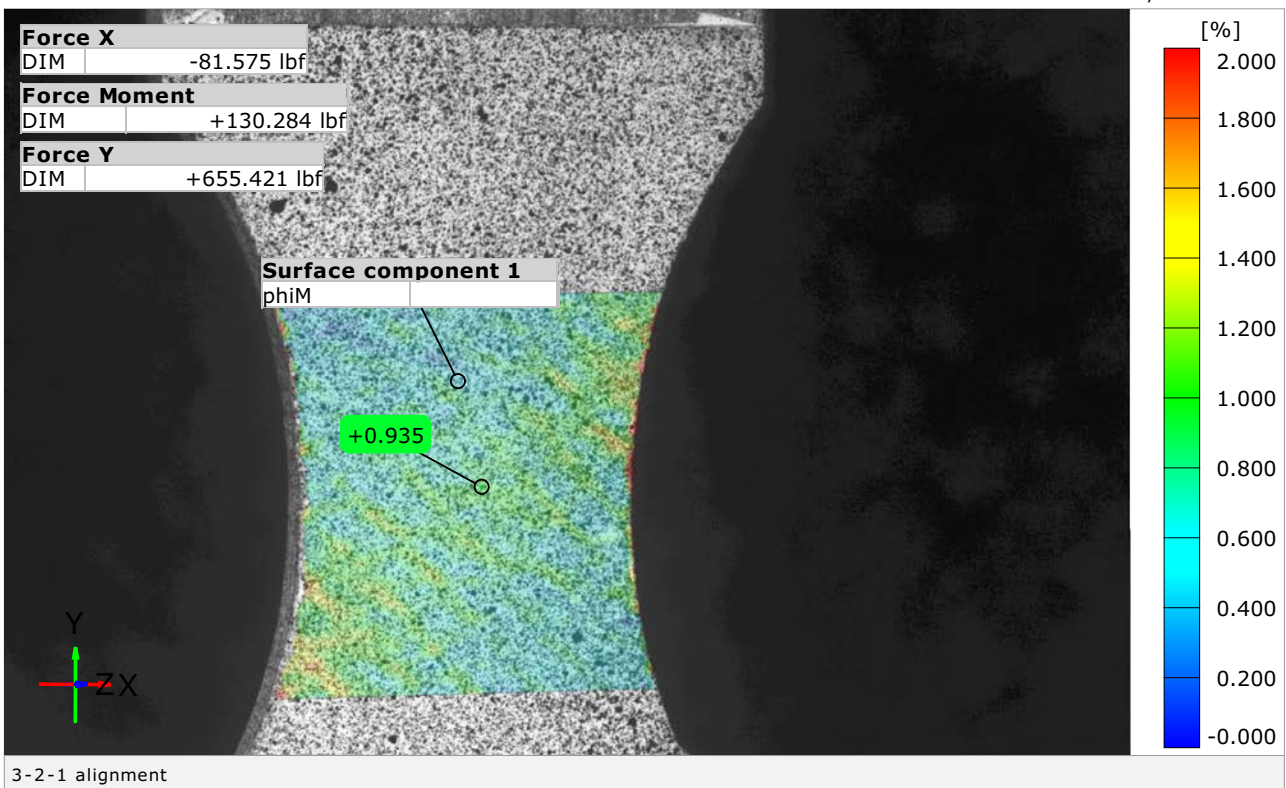
17.07.2024

1/2

Biaxial T6 Further Failure Example (Sample 250)

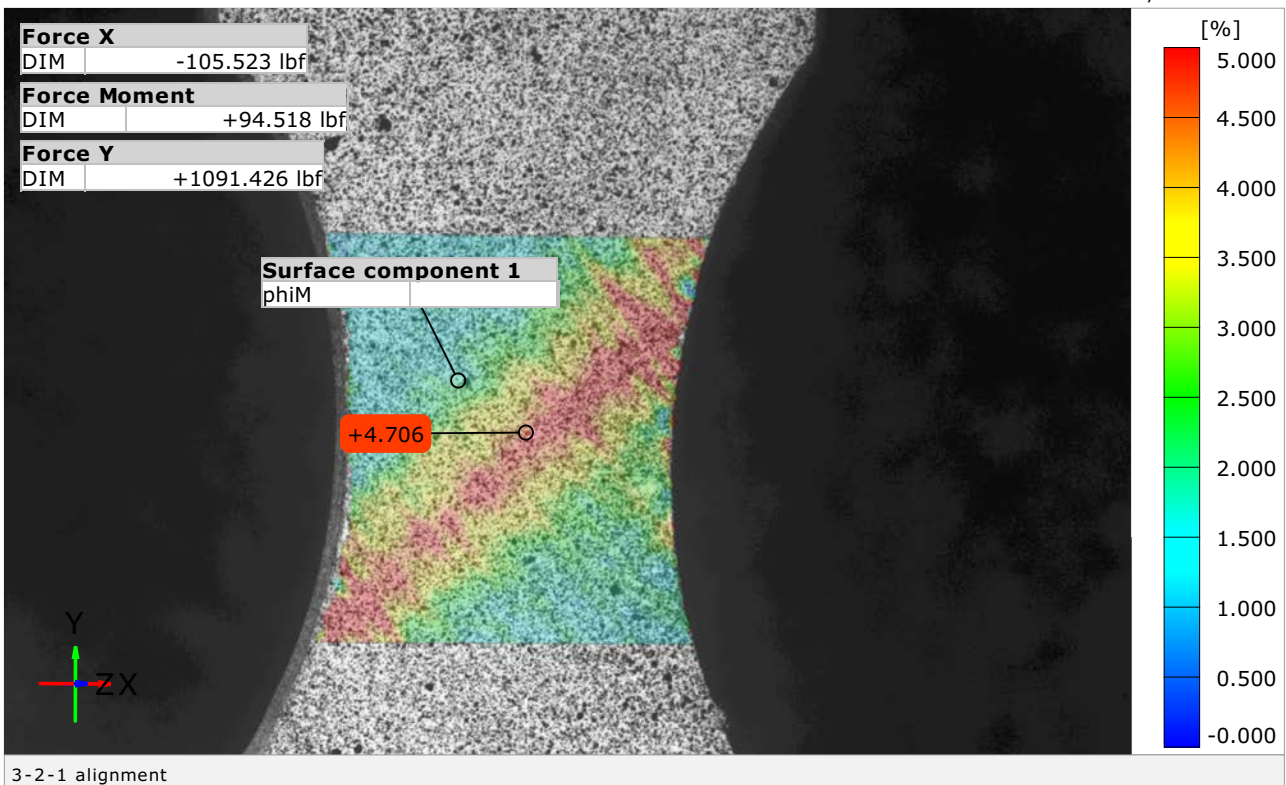
43

Geometry reference: 1



117

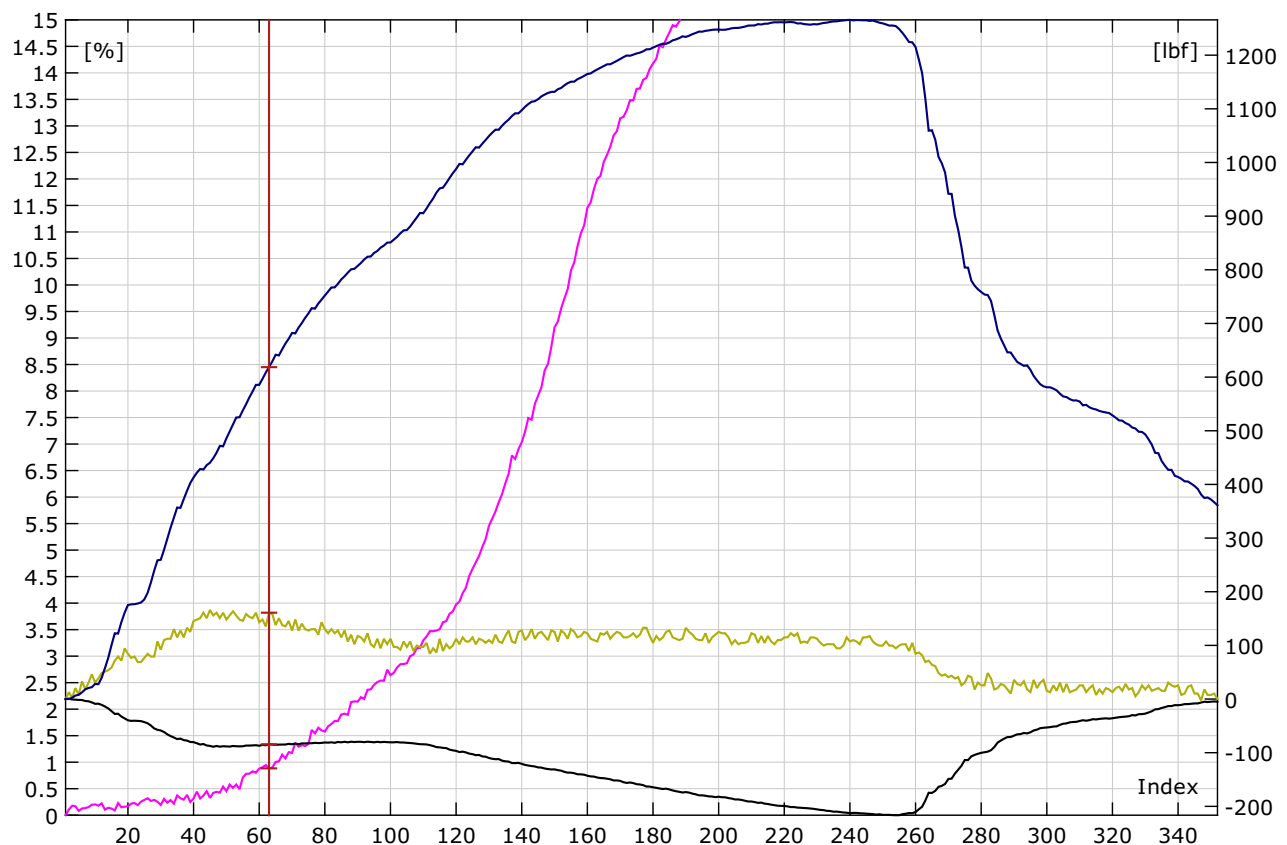
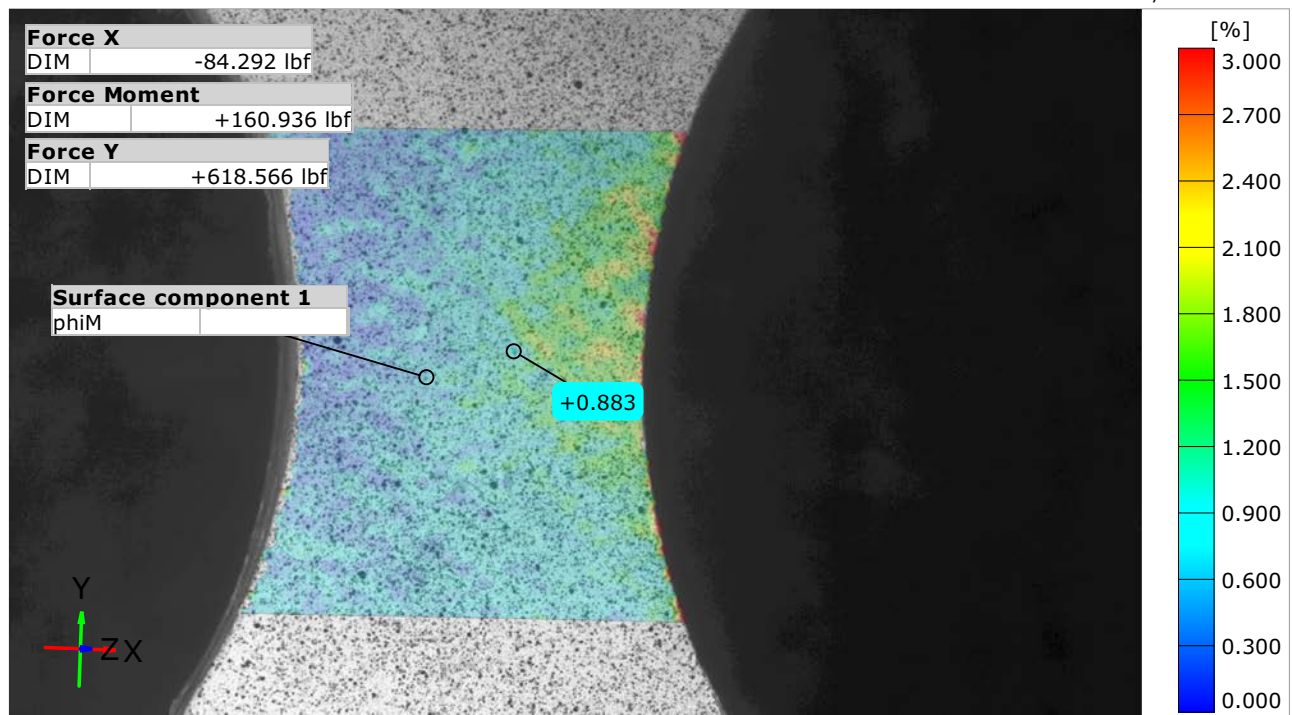
Geometry reference: 1



Biaxial T7 Failure Example (Sample 256)

63

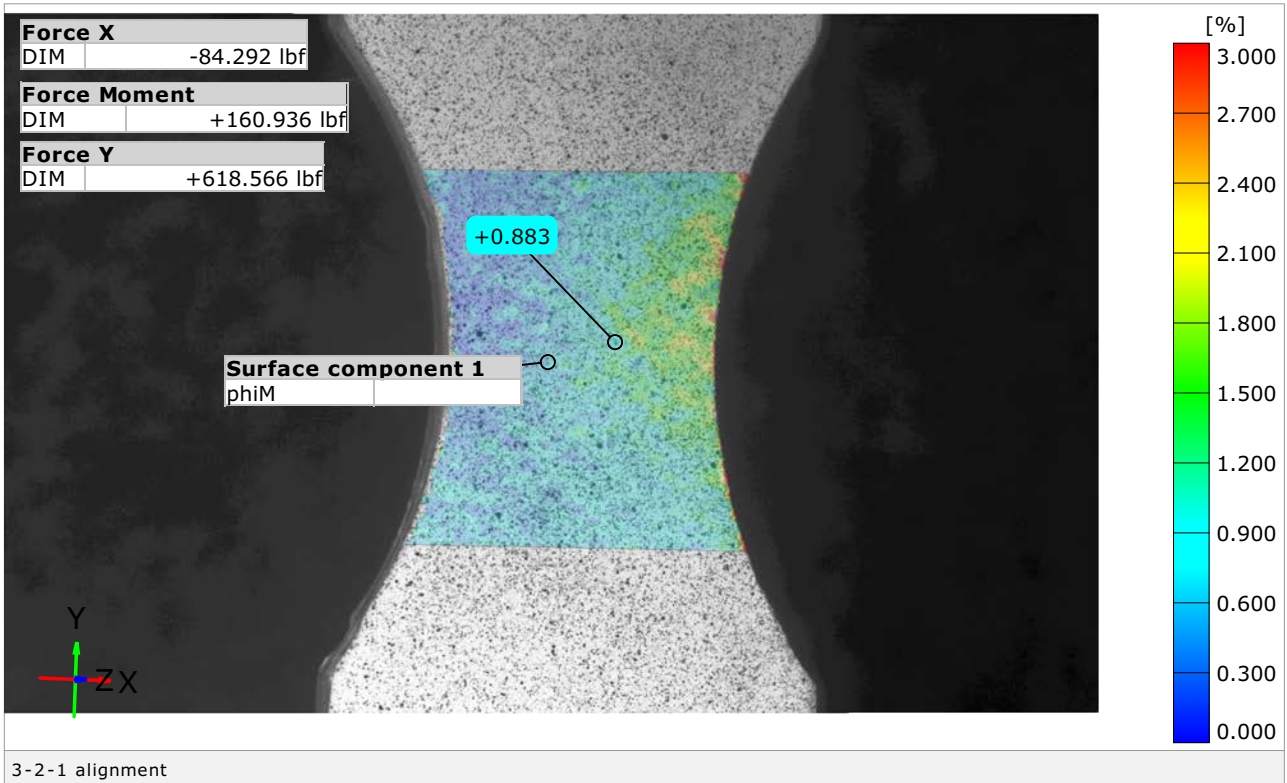
Geometry reference: 1



Biaxial T7 Further Failure Example (Sample 256)

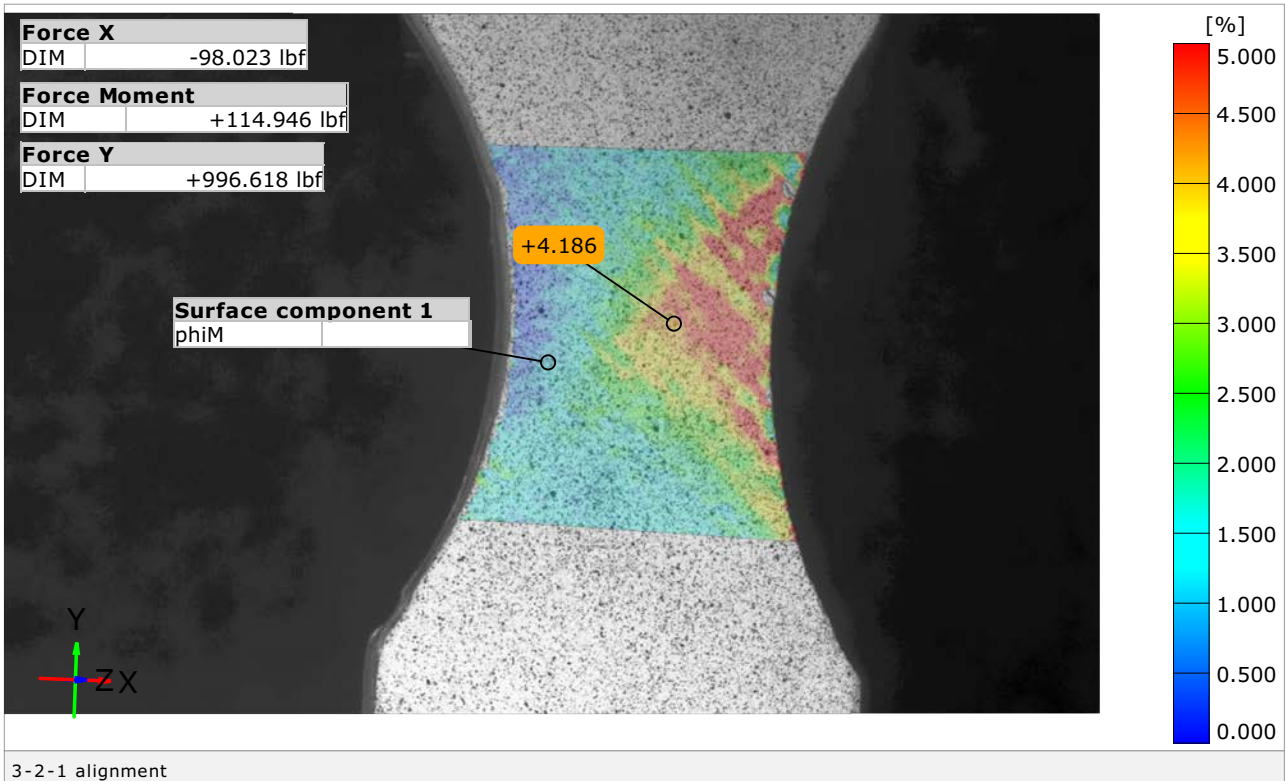
63

Geometry reference: 1



122

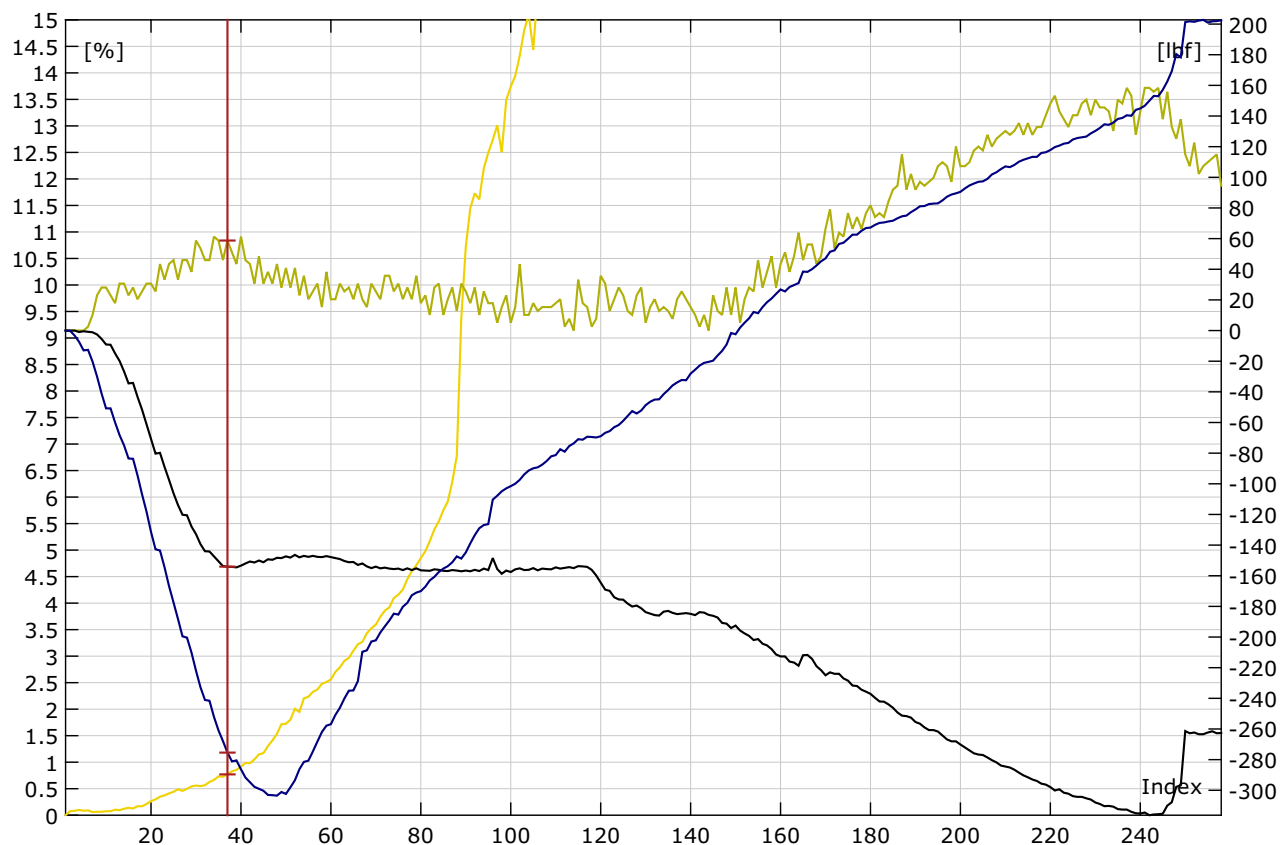
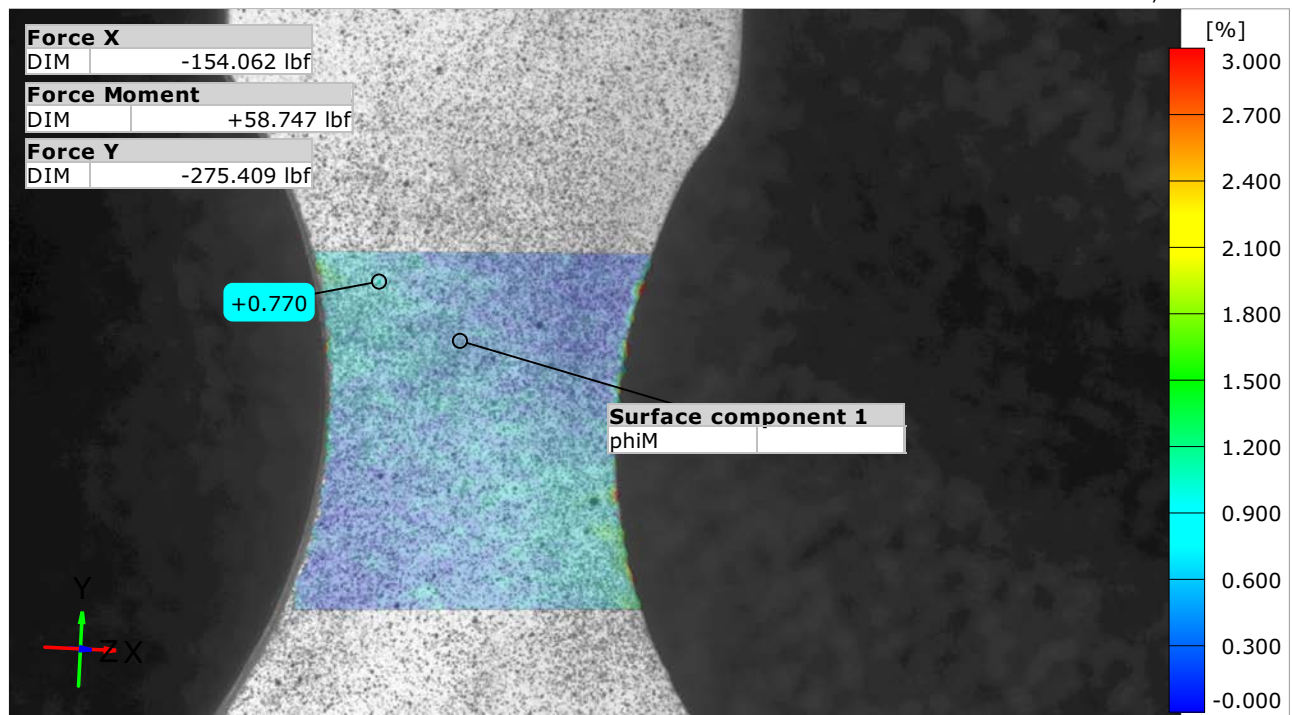
Geometry reference: 1



Biaxial T8 Failure Example (Sample 260)

37

Geometry reference: 1



3-2-1 alignment

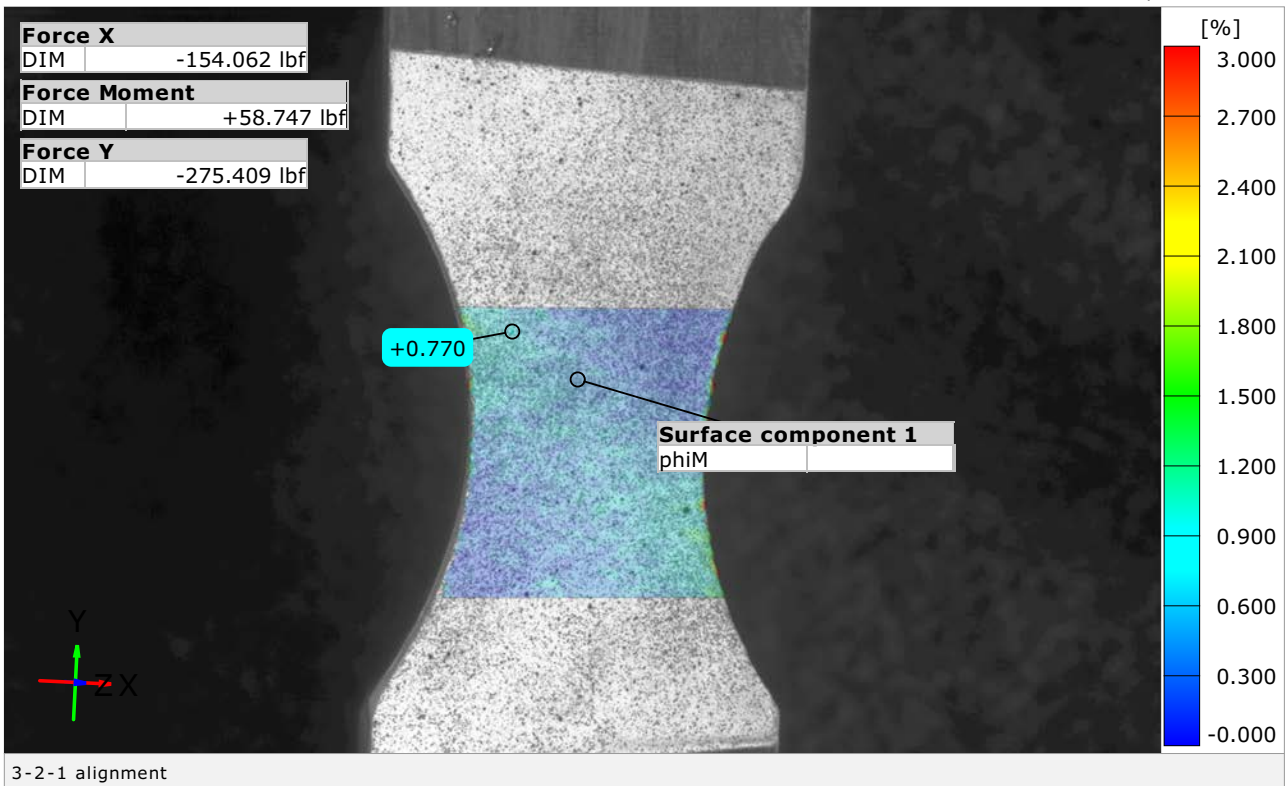
25.07.2024

3/4

Biaxial T8 Further Failure Example (Sample 260)

37

Geometry reference: 1



66

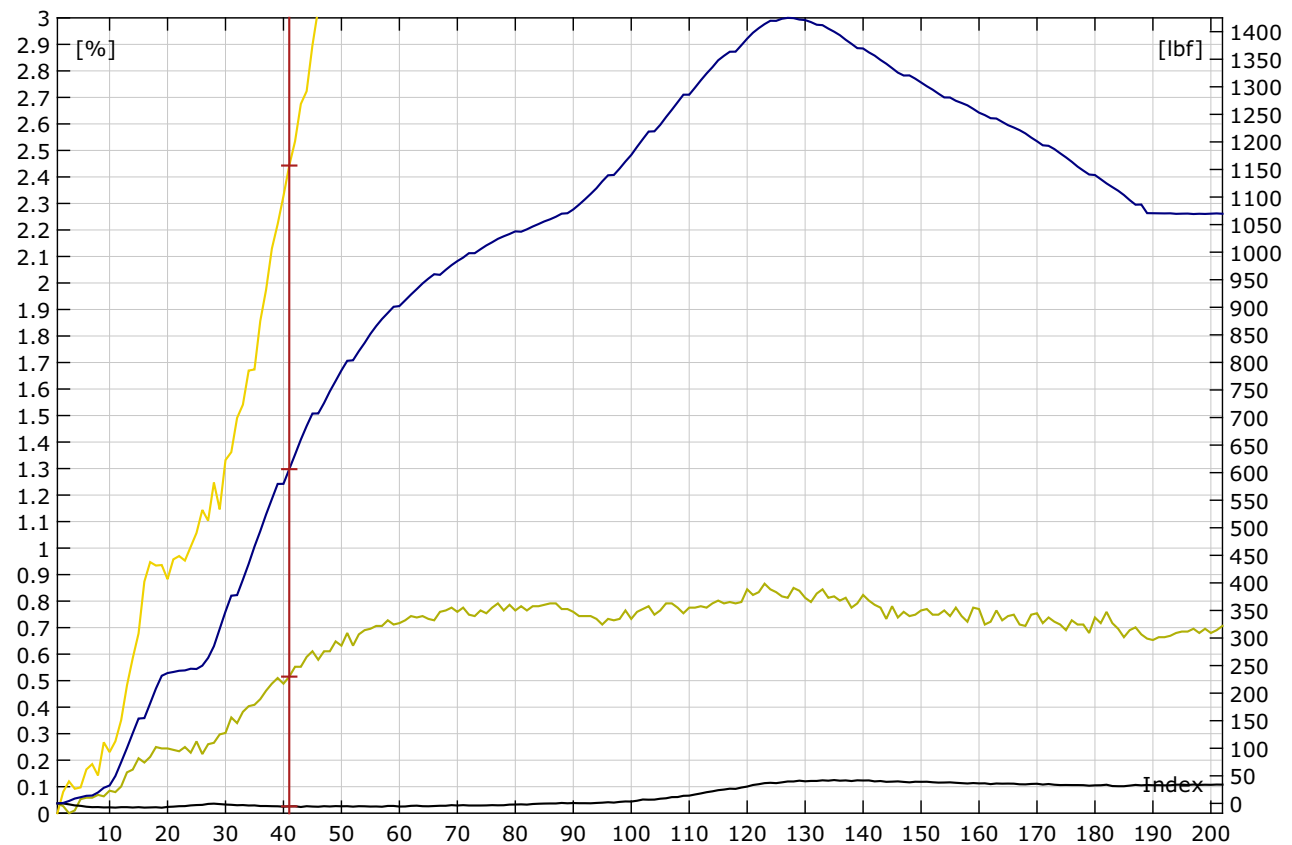
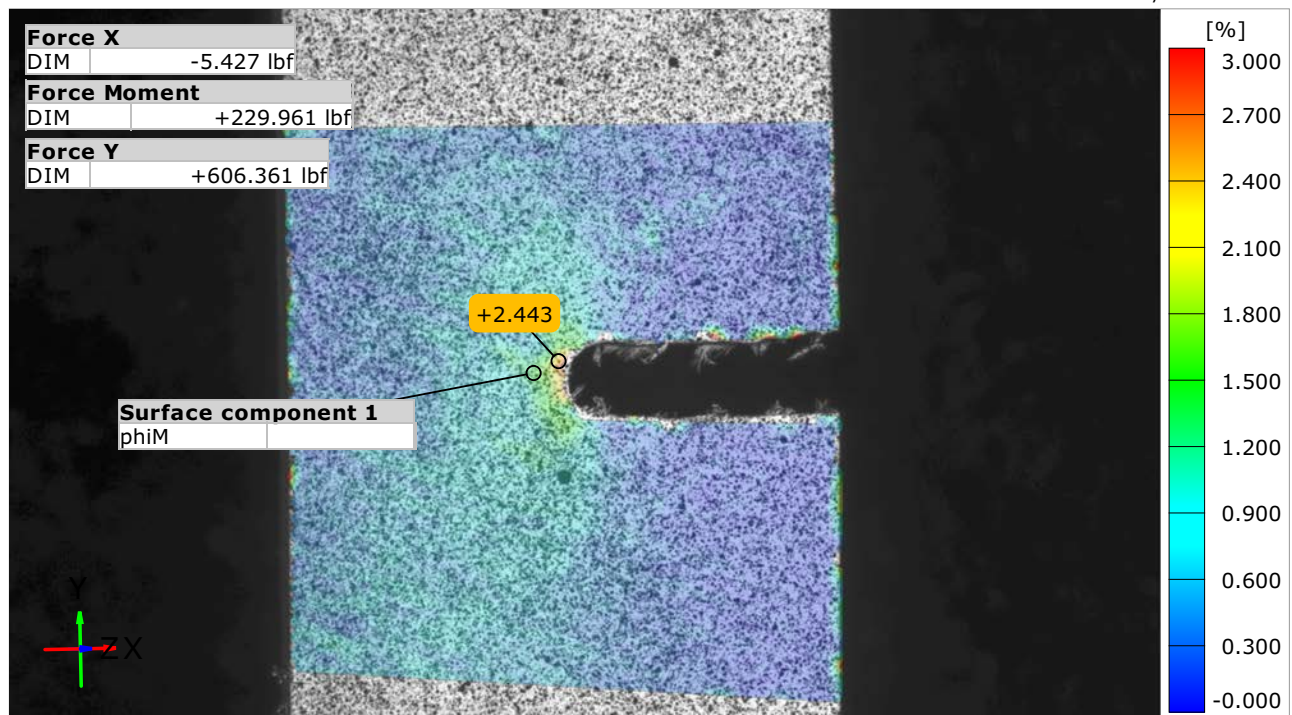
Geometry reference: 1



Triaxial T1 Failure Example (Sample 306)

41

Geometry reference: 1

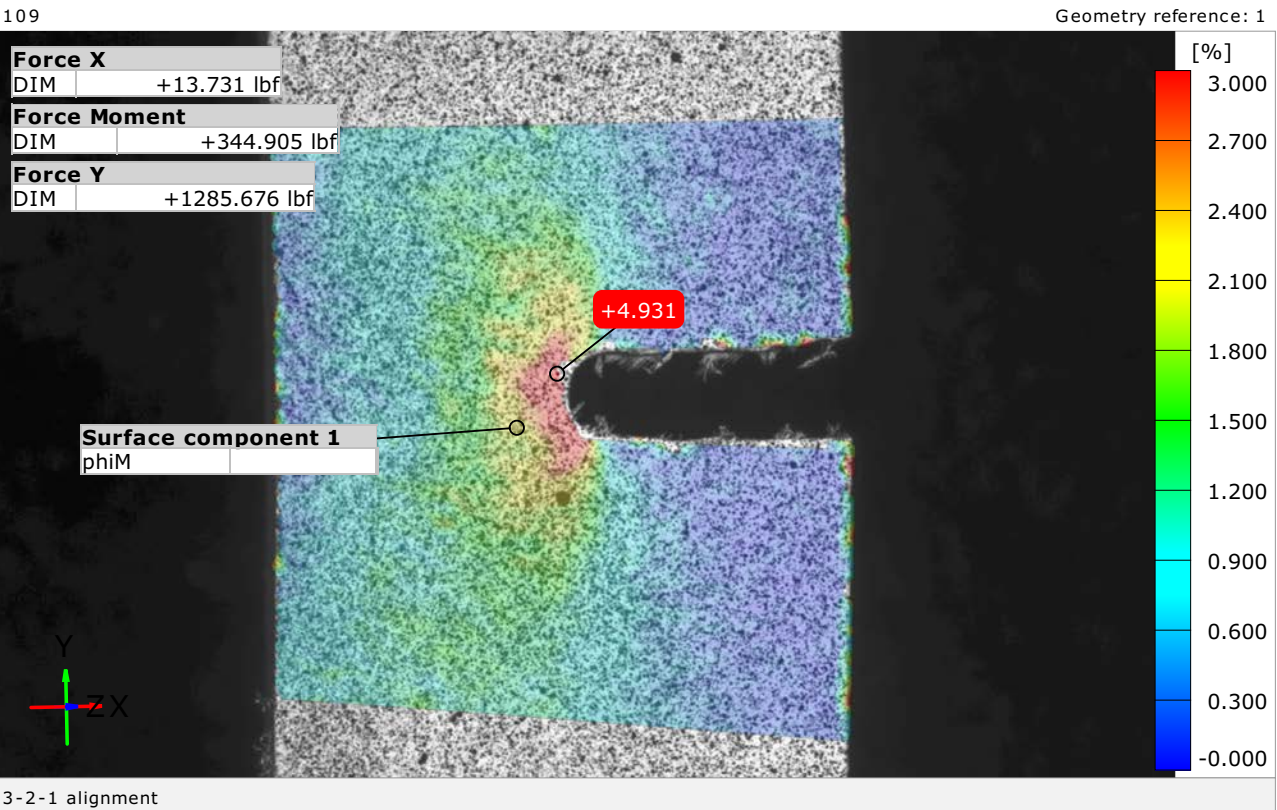
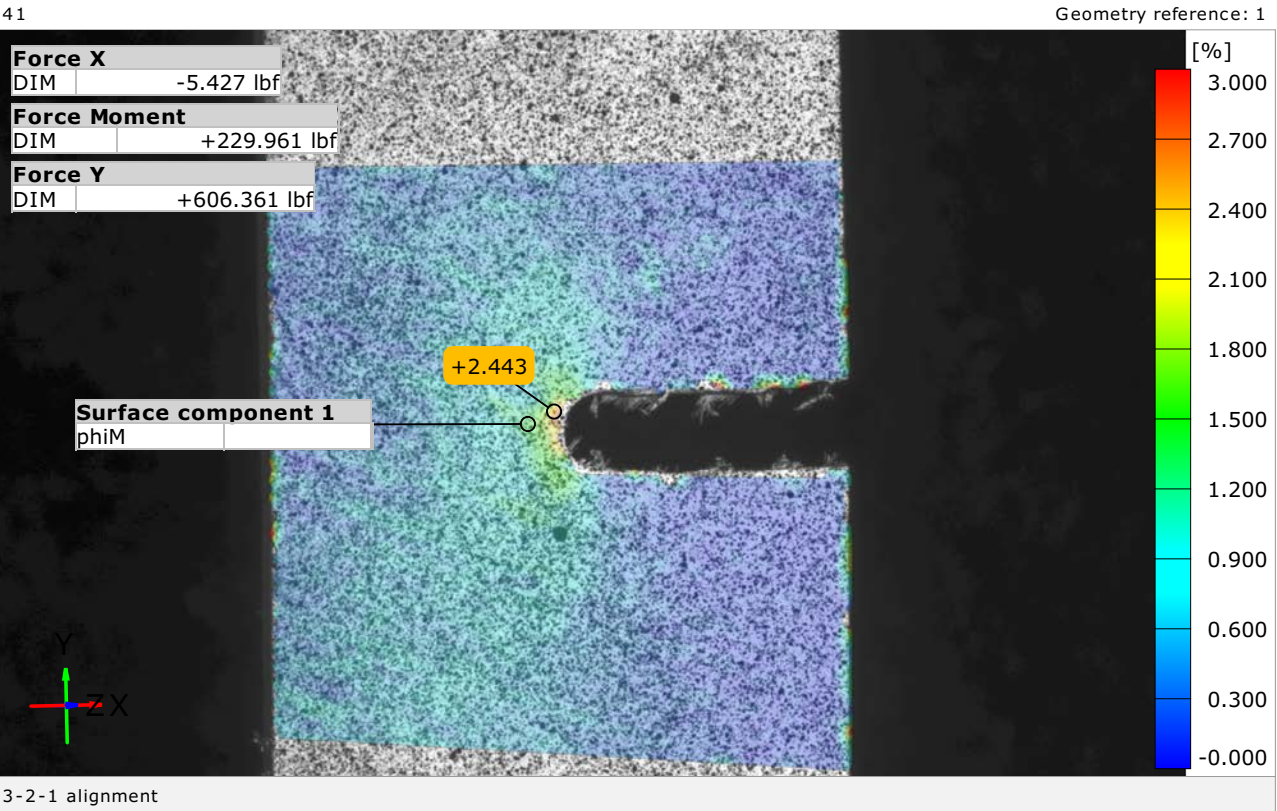


3-2-1 alignment

22.07.2024

1/2

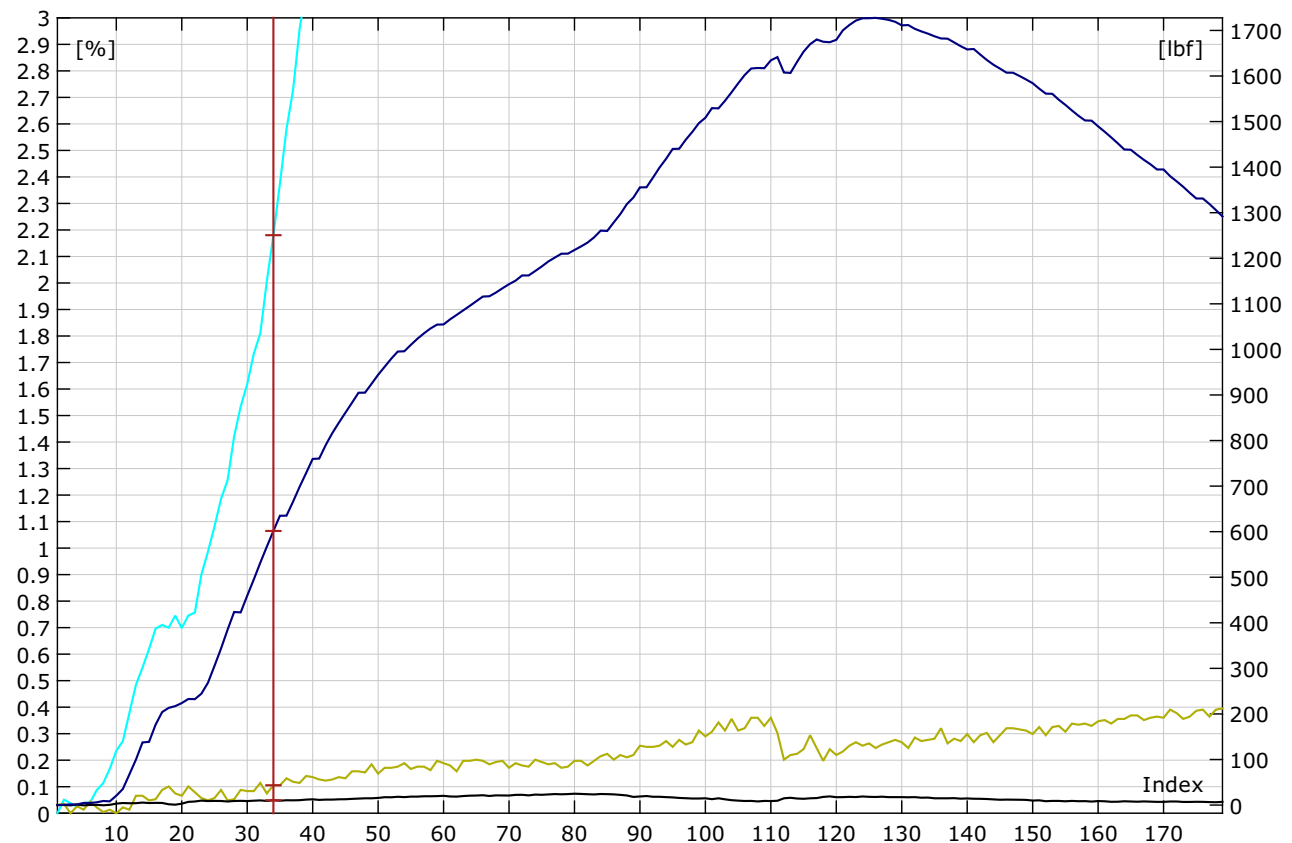
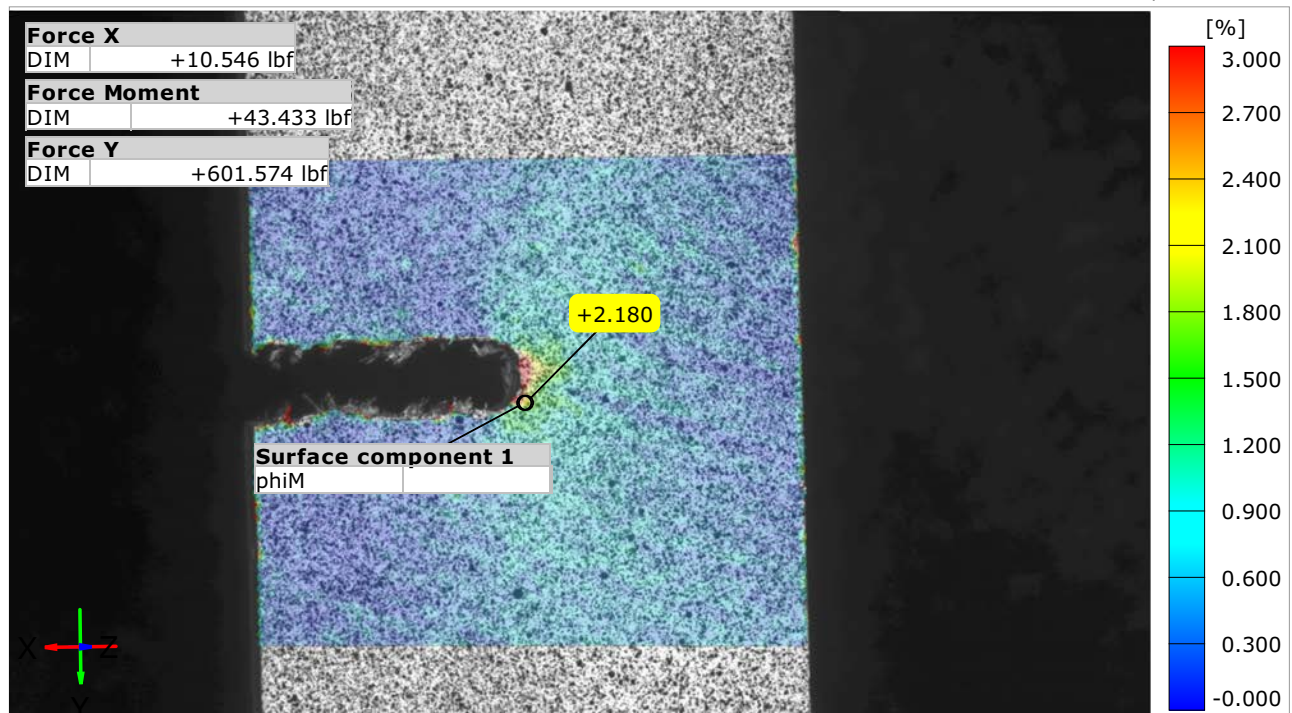
Triaxial T1 Further Failure Example (Sample 306)



Triaxial T2 Failure Example (Sample 307)

34

Geometry reference: 1



3-2-1 alignment

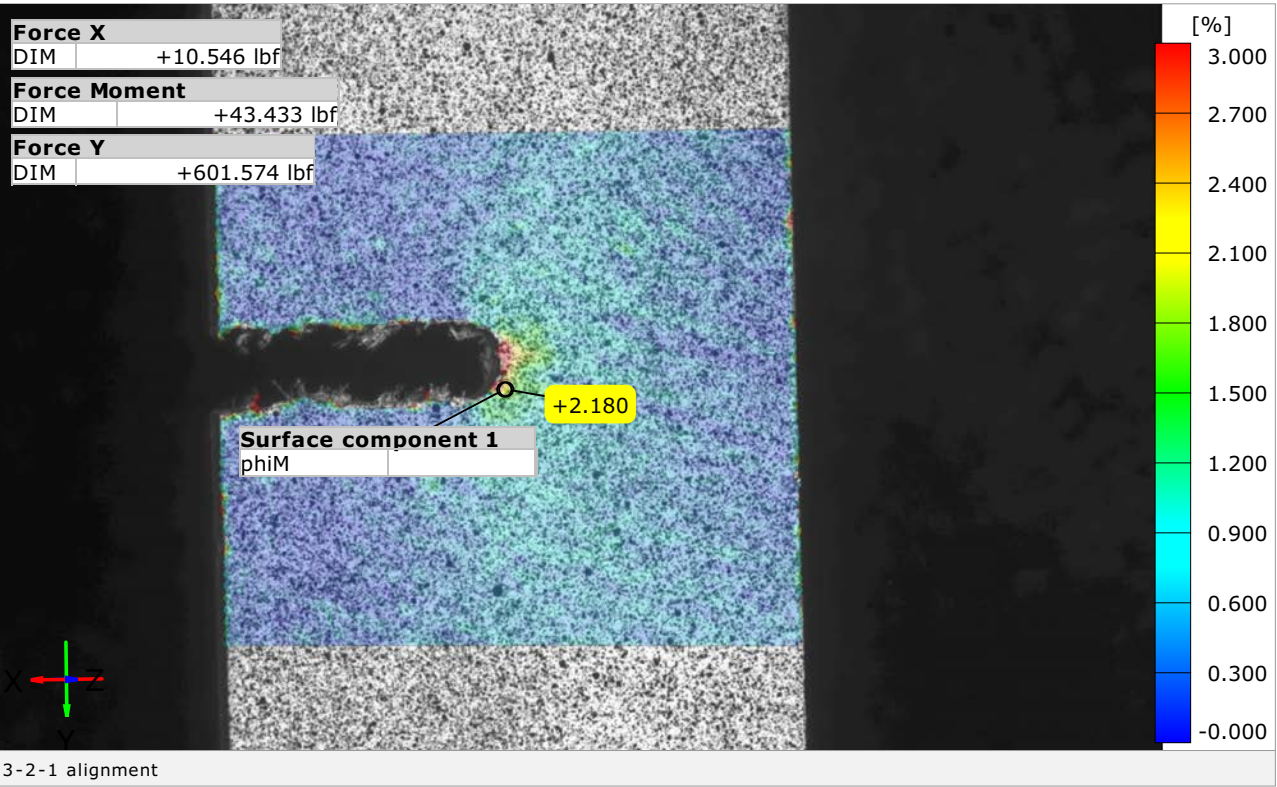
22.07.2024

1/2

Triaxial T2 Further Failure Example (Sample 307)

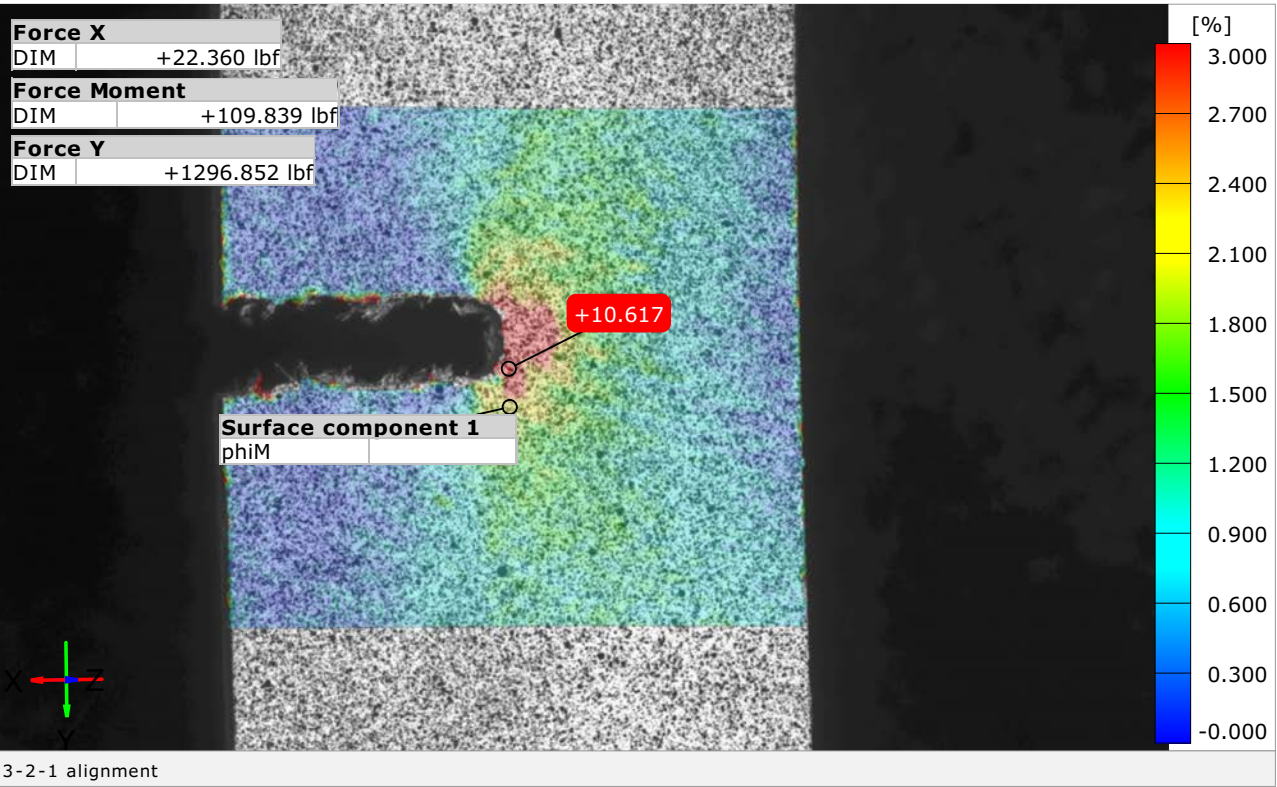
34

Geometry reference: 1



87

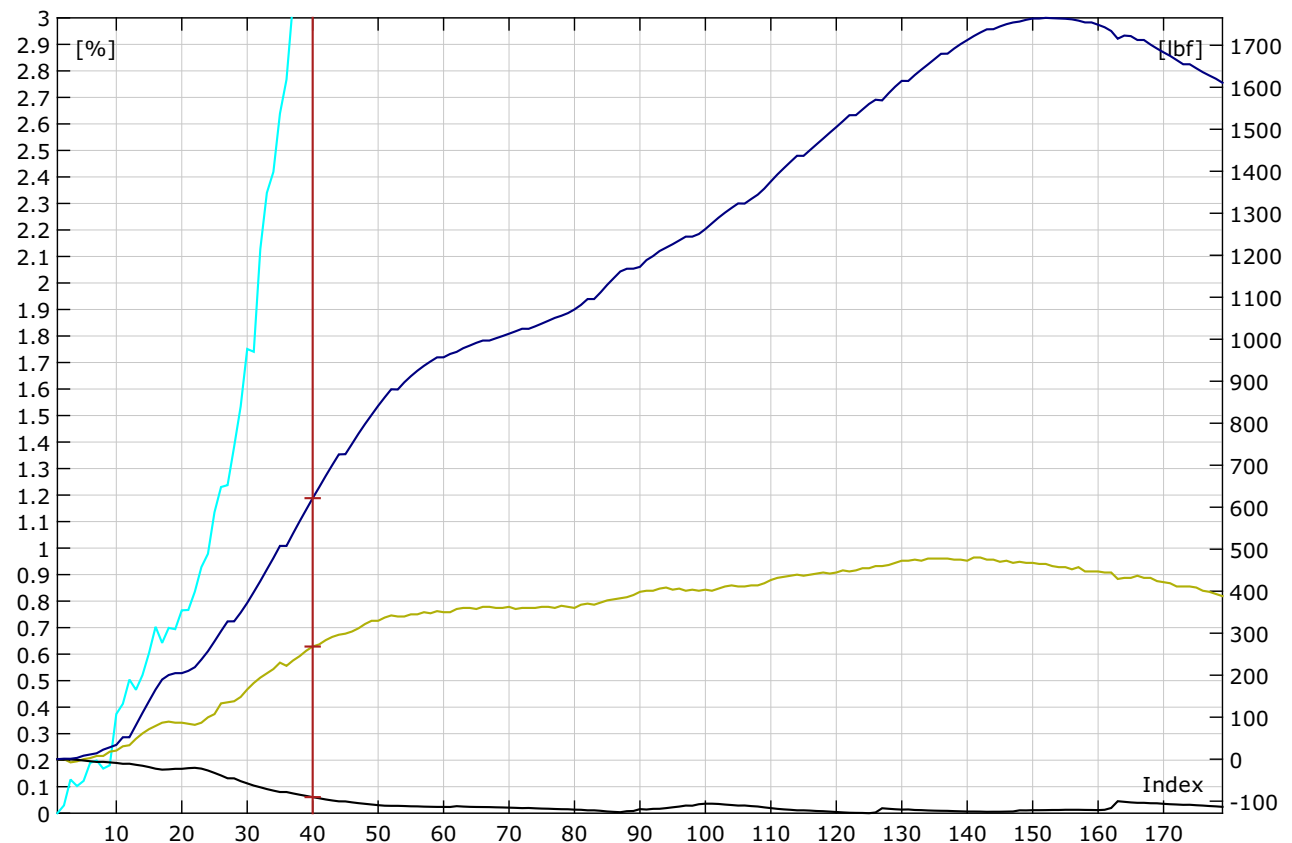
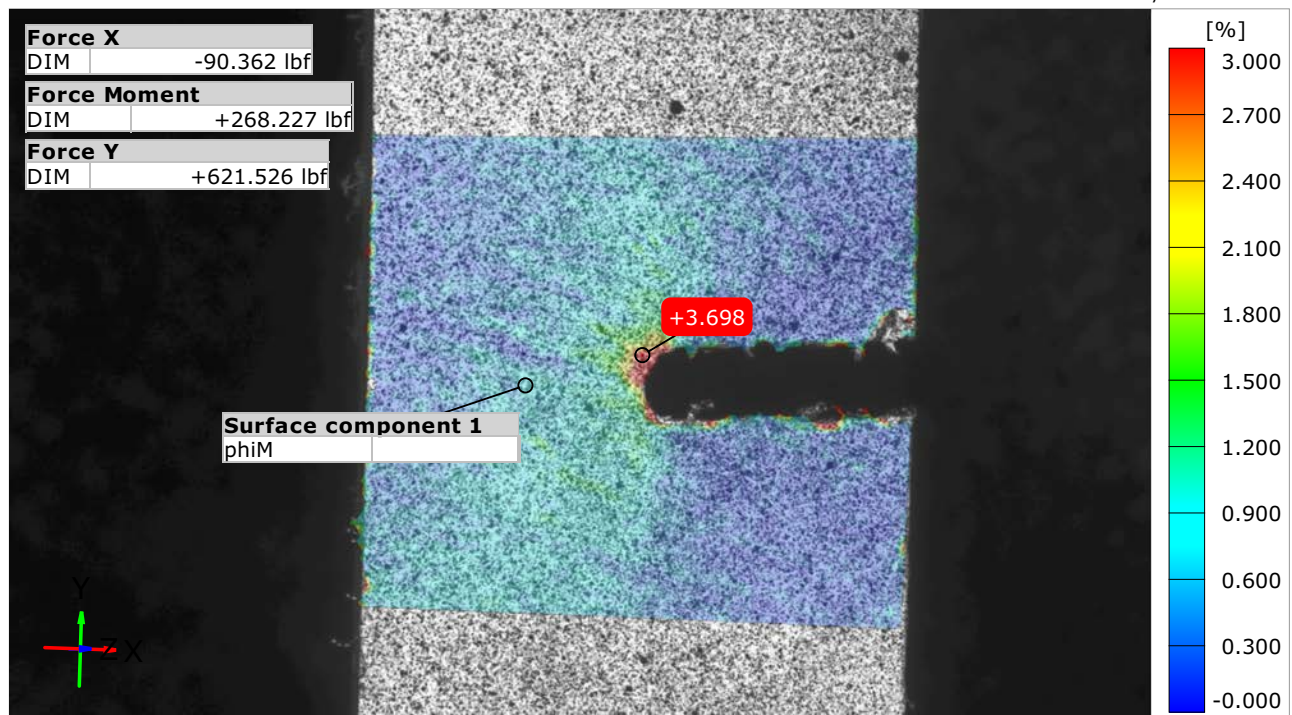
Geometry reference: 1



Triaxial T3 Failure Example (Sample 304)

40

Geometry reference: 1



3-2-1 alignment

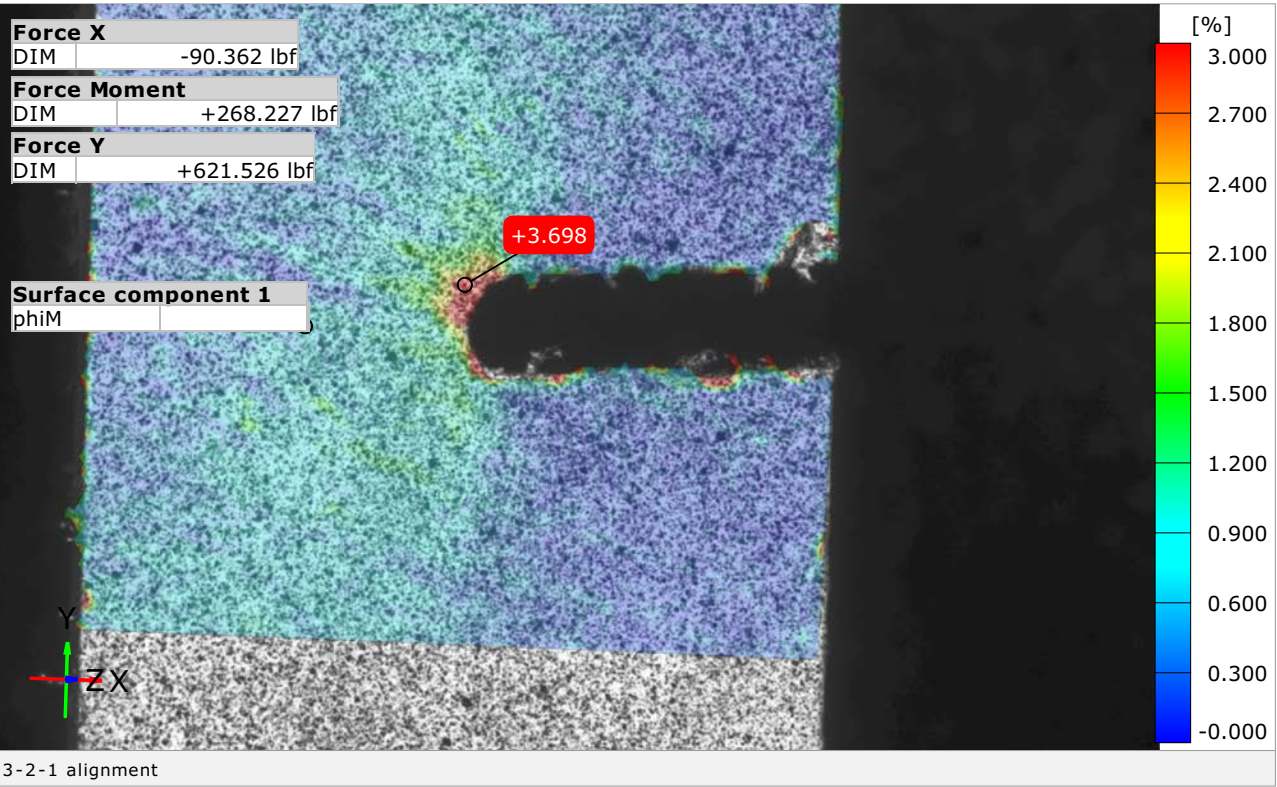
23.07.2024

1/2

Triaxial T3 Further Failure Example (Sample 304)

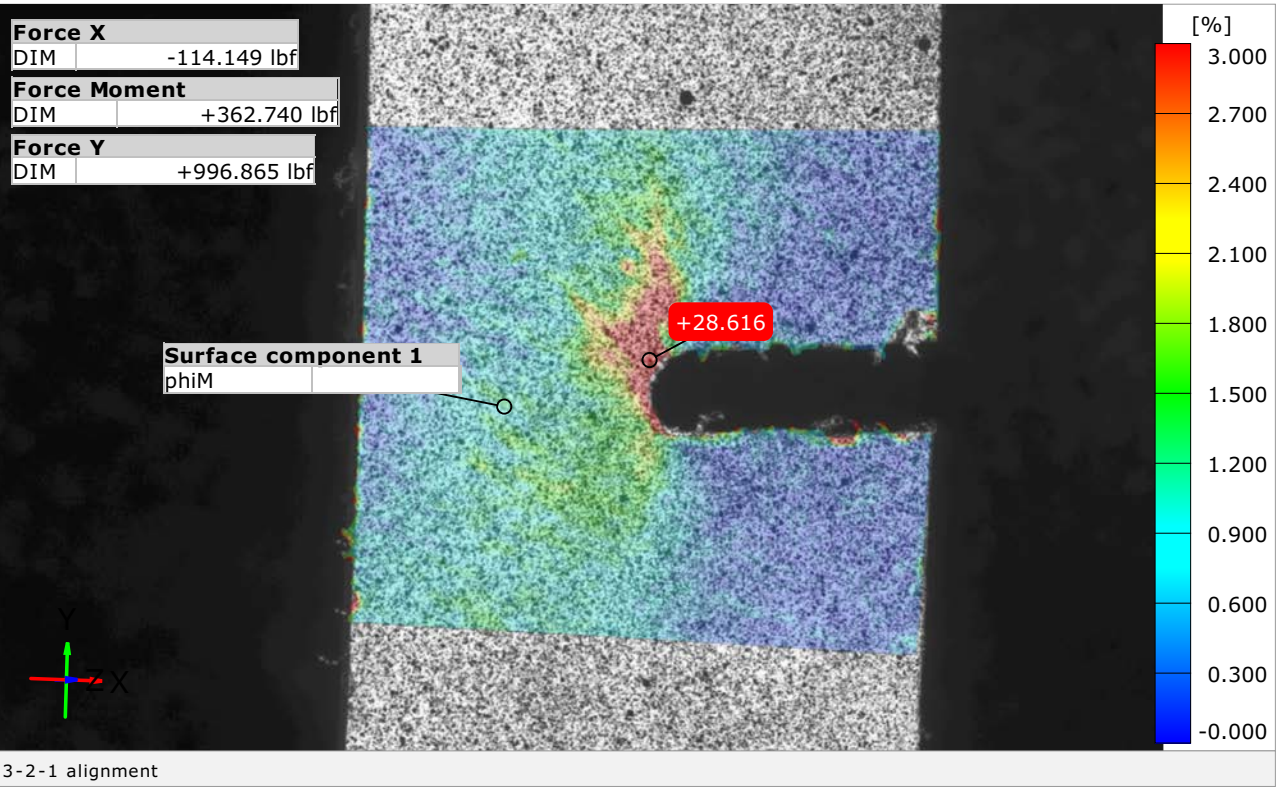
40

Geometry reference: 1



67

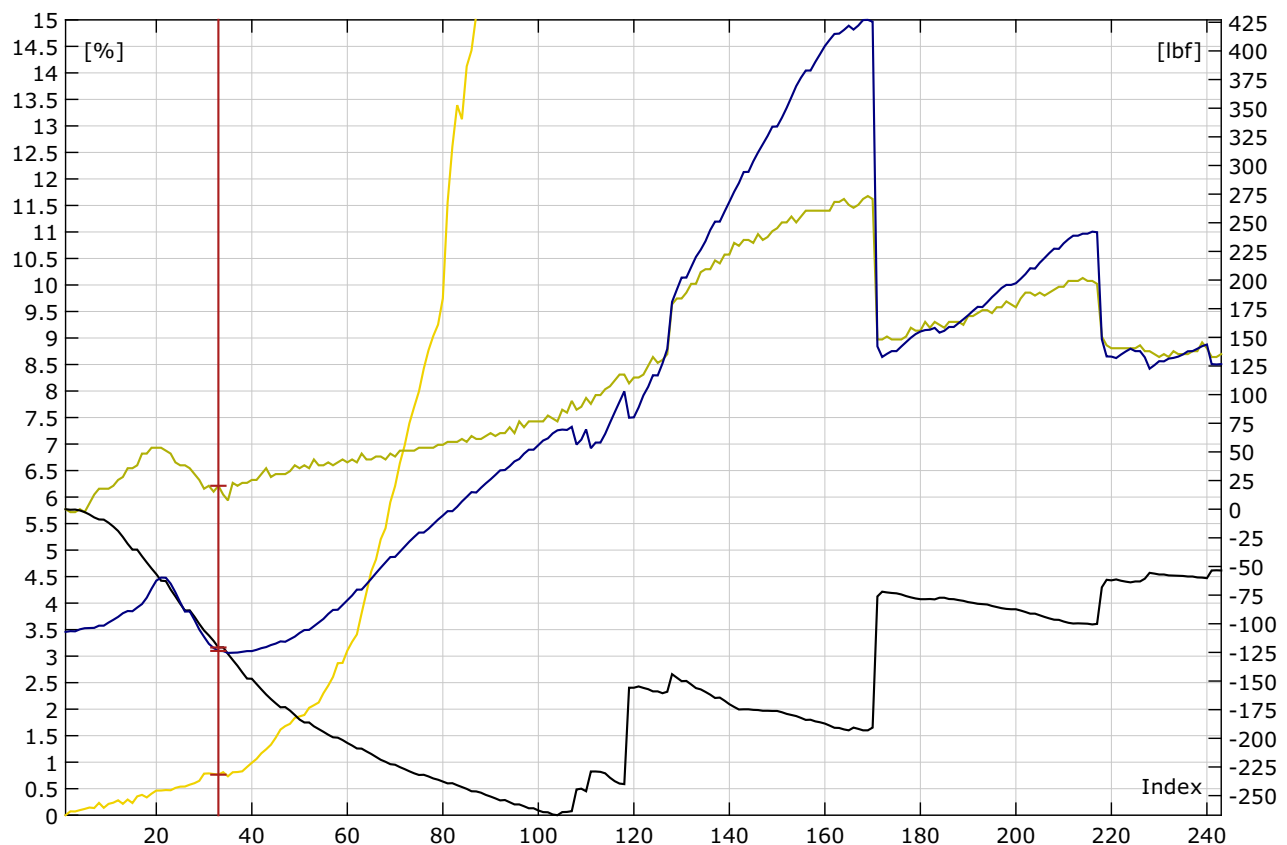
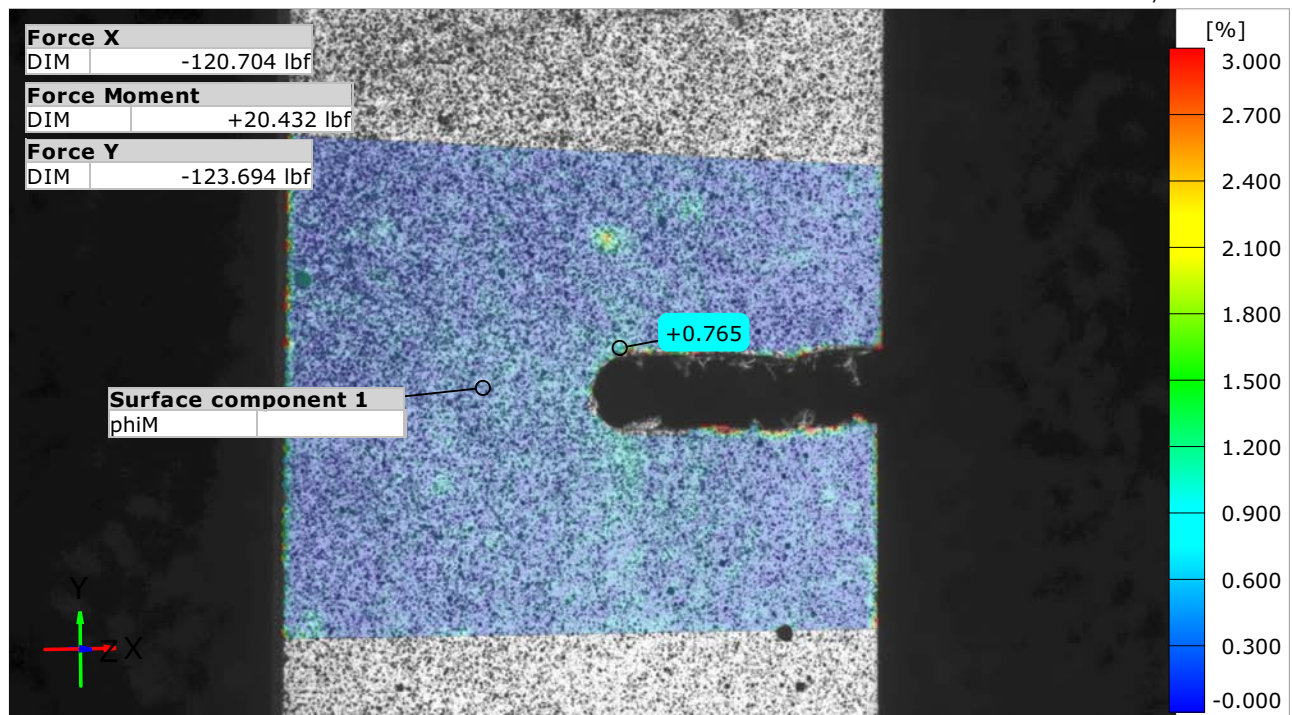
Geometry reference: 1



Triaxial T4 Failure Example (Sample 309)

33

Geometry reference: 1



3-2-1 alignment

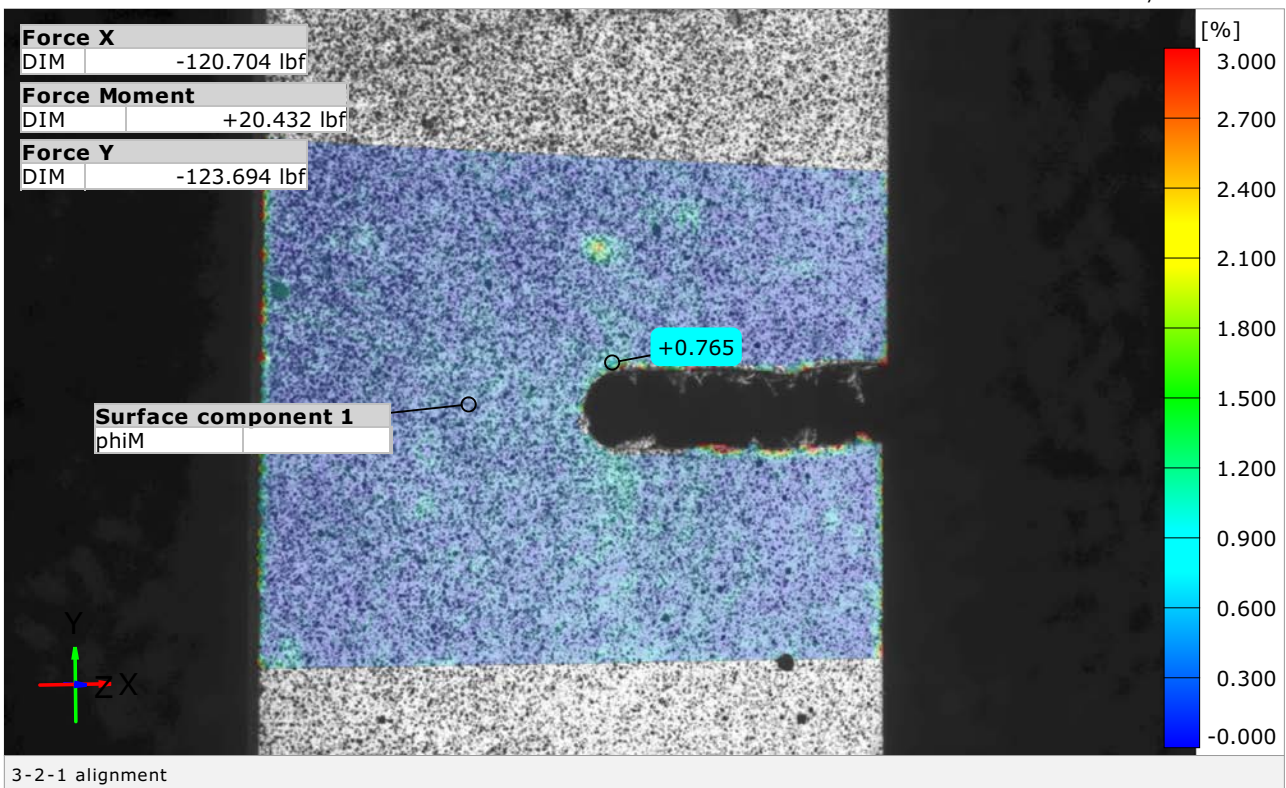
23.07.2024

3/4

Triaxial T4 Further Failure Example (Sample 309)

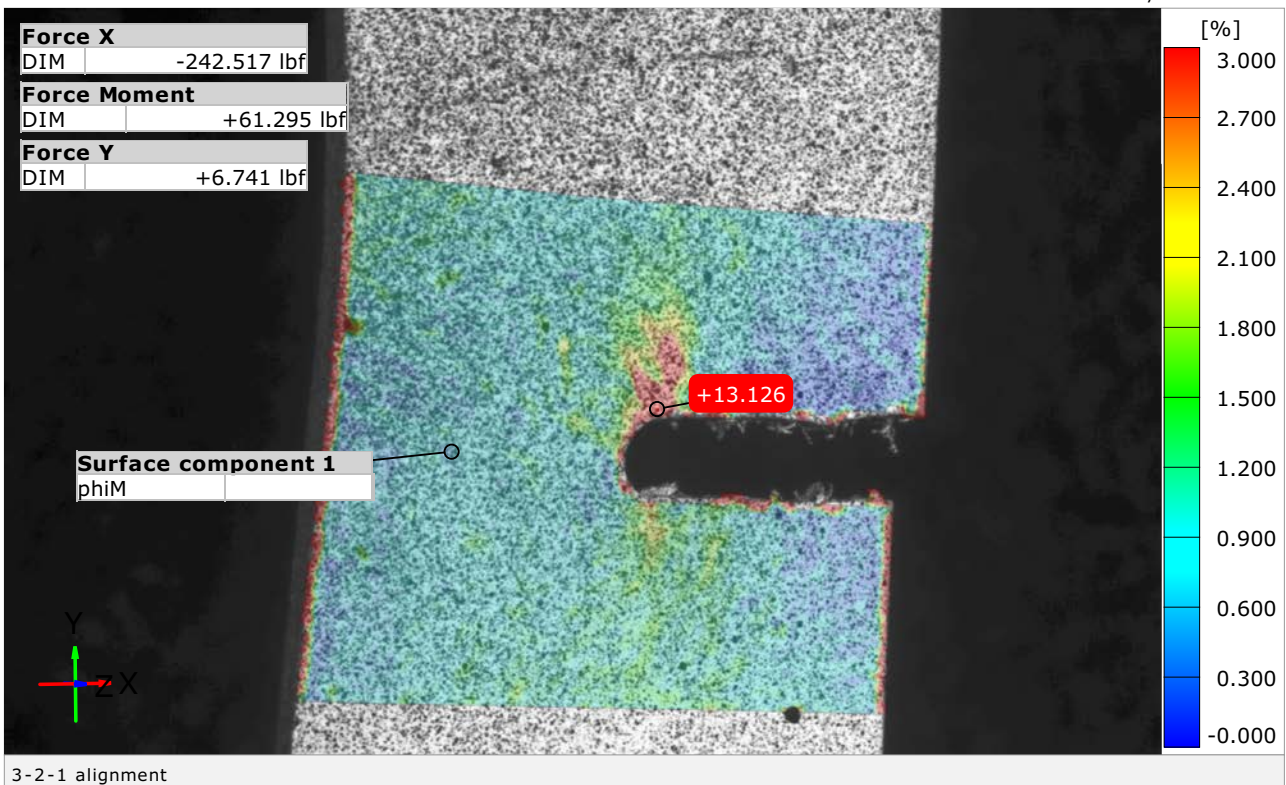
33

Geometry reference: 1



84

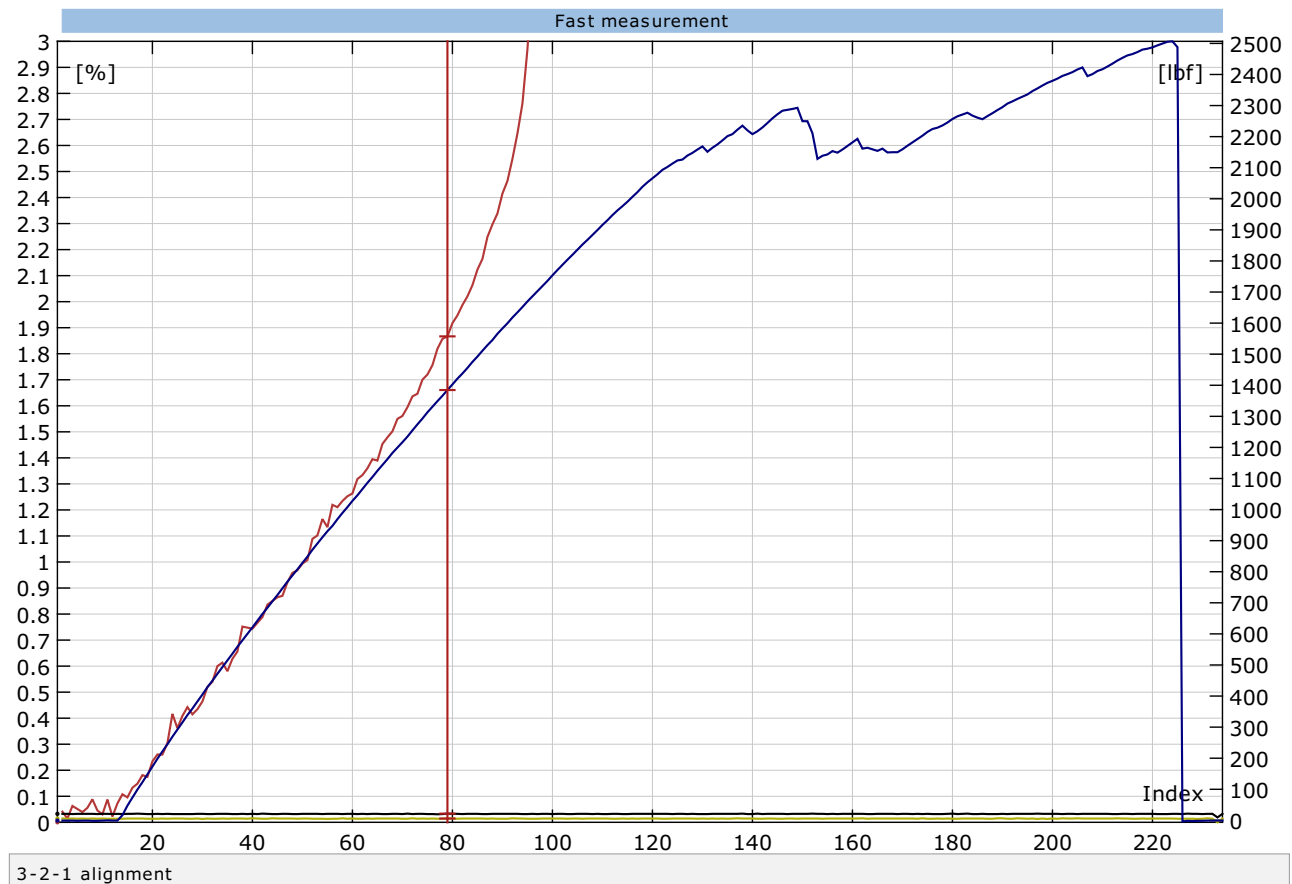
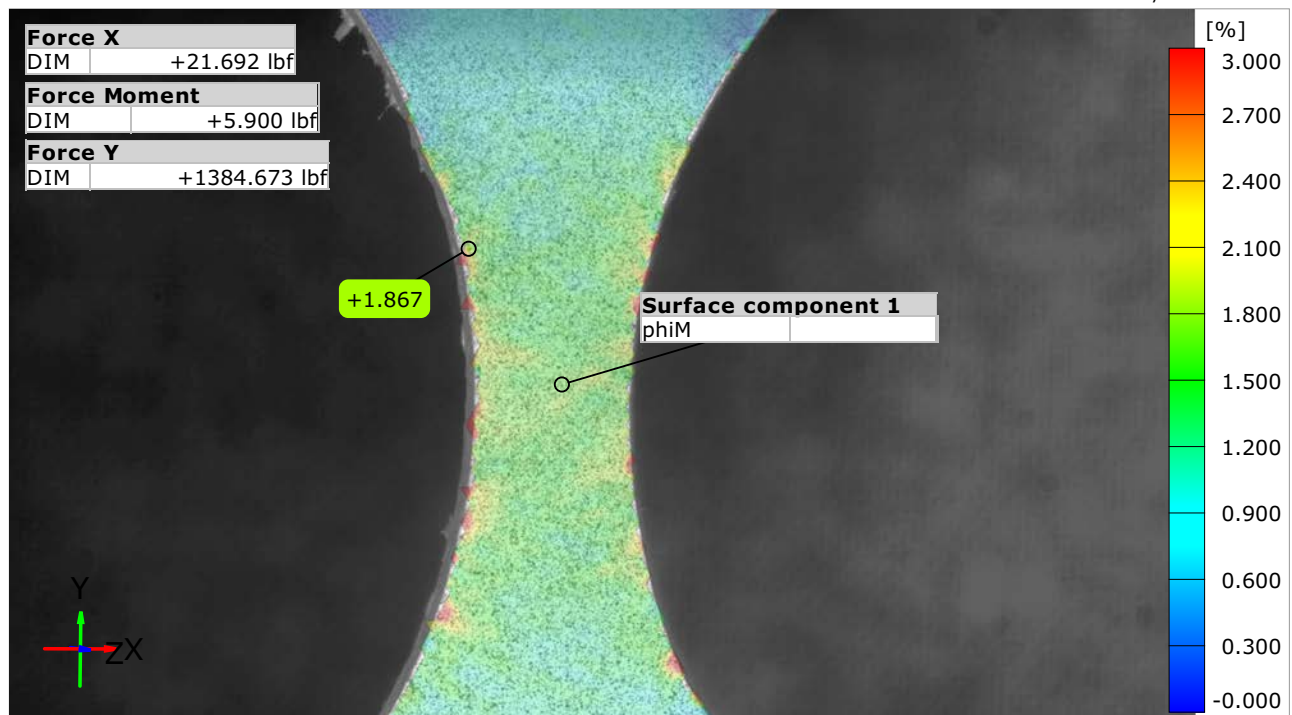
Geometry reference: 1



Triaxial T5 Failure Example (Sample 334)

79

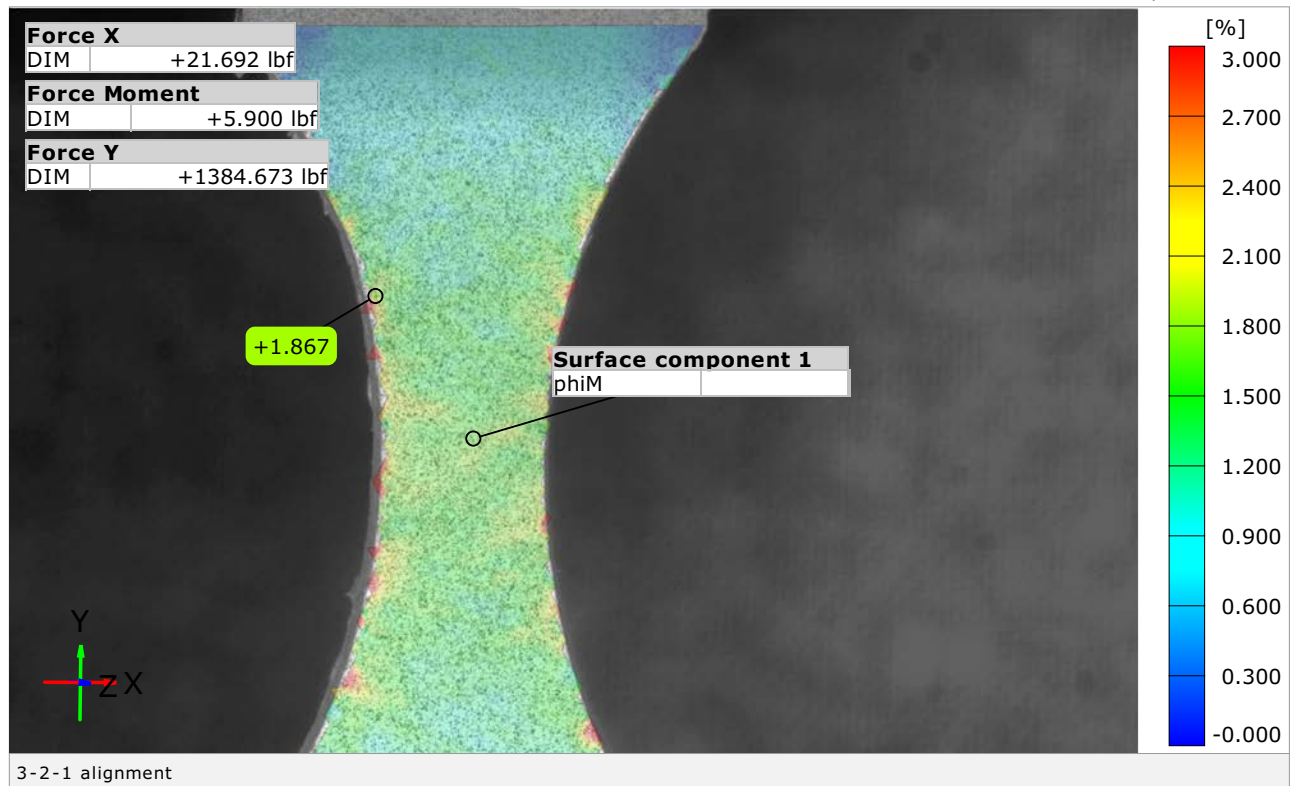
Geometry reference: 1



Triaxial T5 Further Failure Example (Sample 334)

79

Geometry reference: 1



103

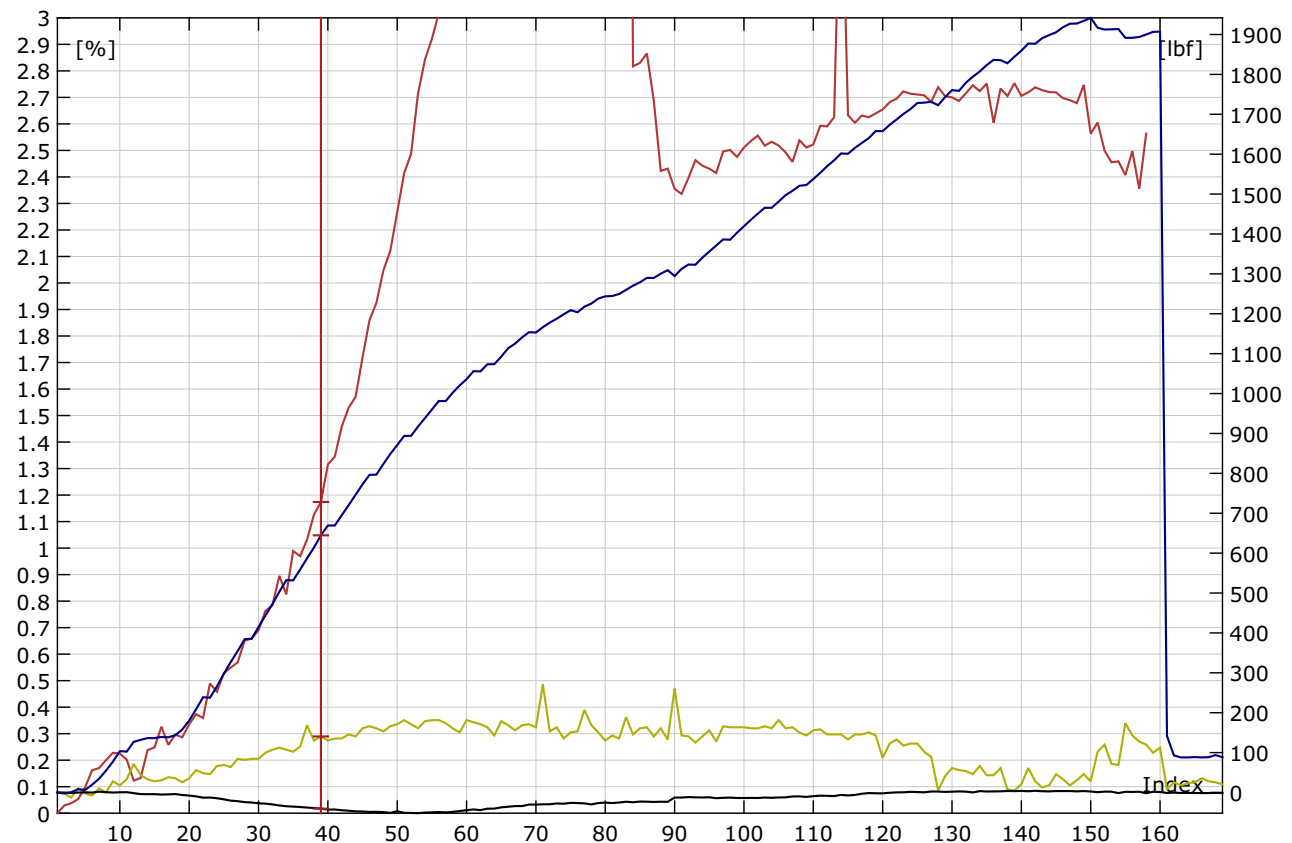
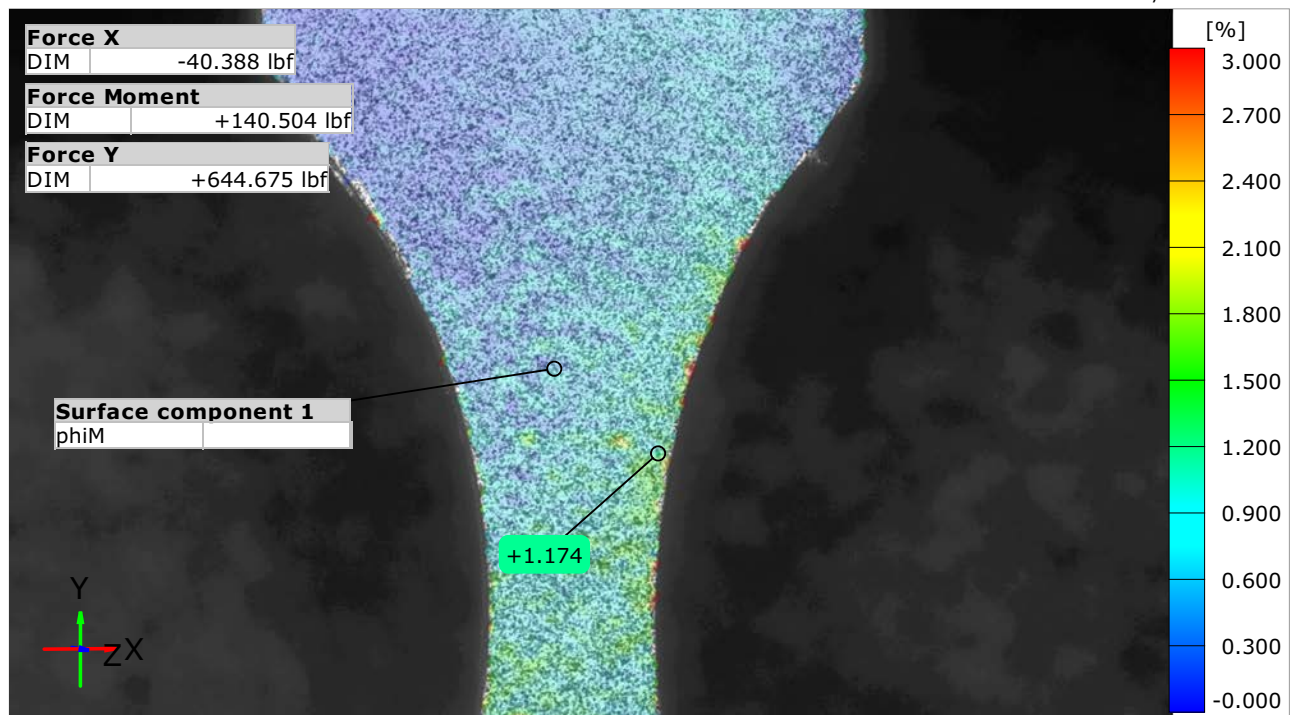
Geometry reference: 1



Triaxial T6 Failure Example (Sample 352)

39

Geometry reference: 1



3-2-1 alignment

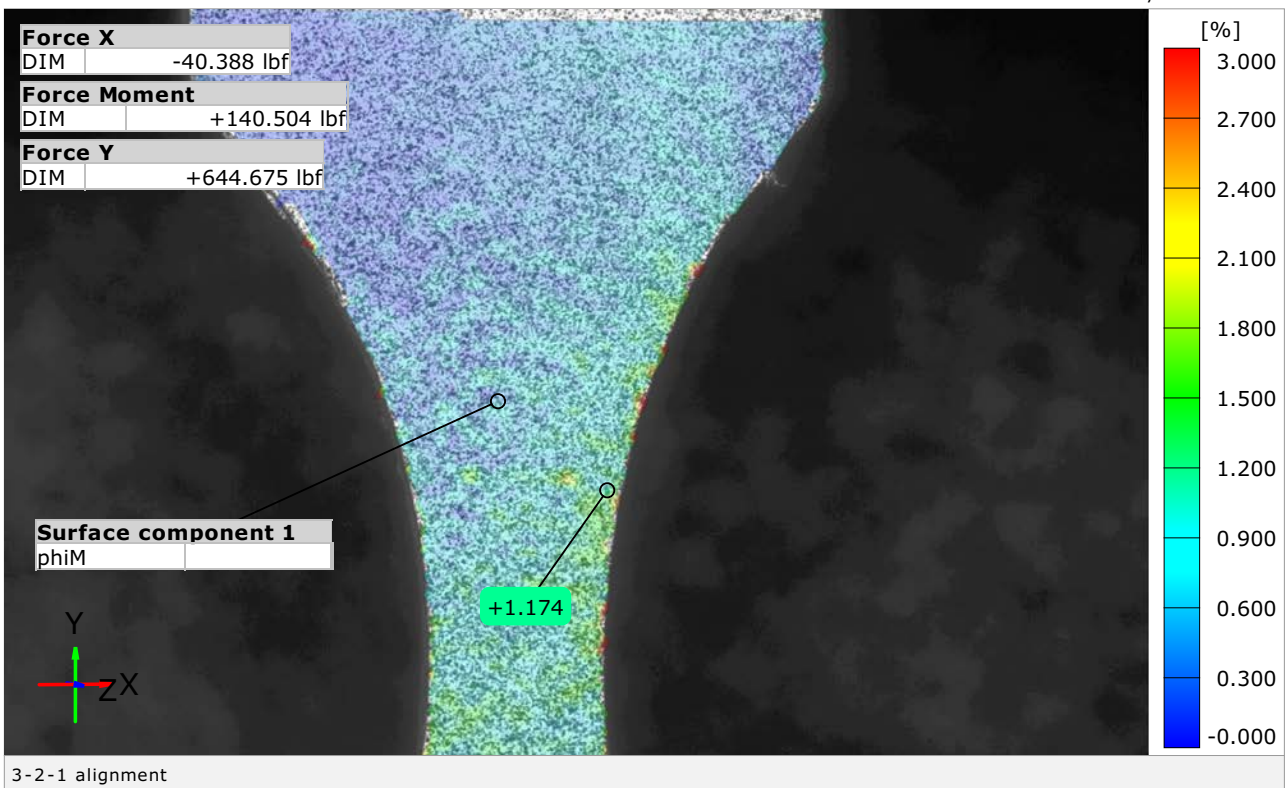
26.02.2025

1/2

Triaxial T6 Further Failure Example (Sample 352)

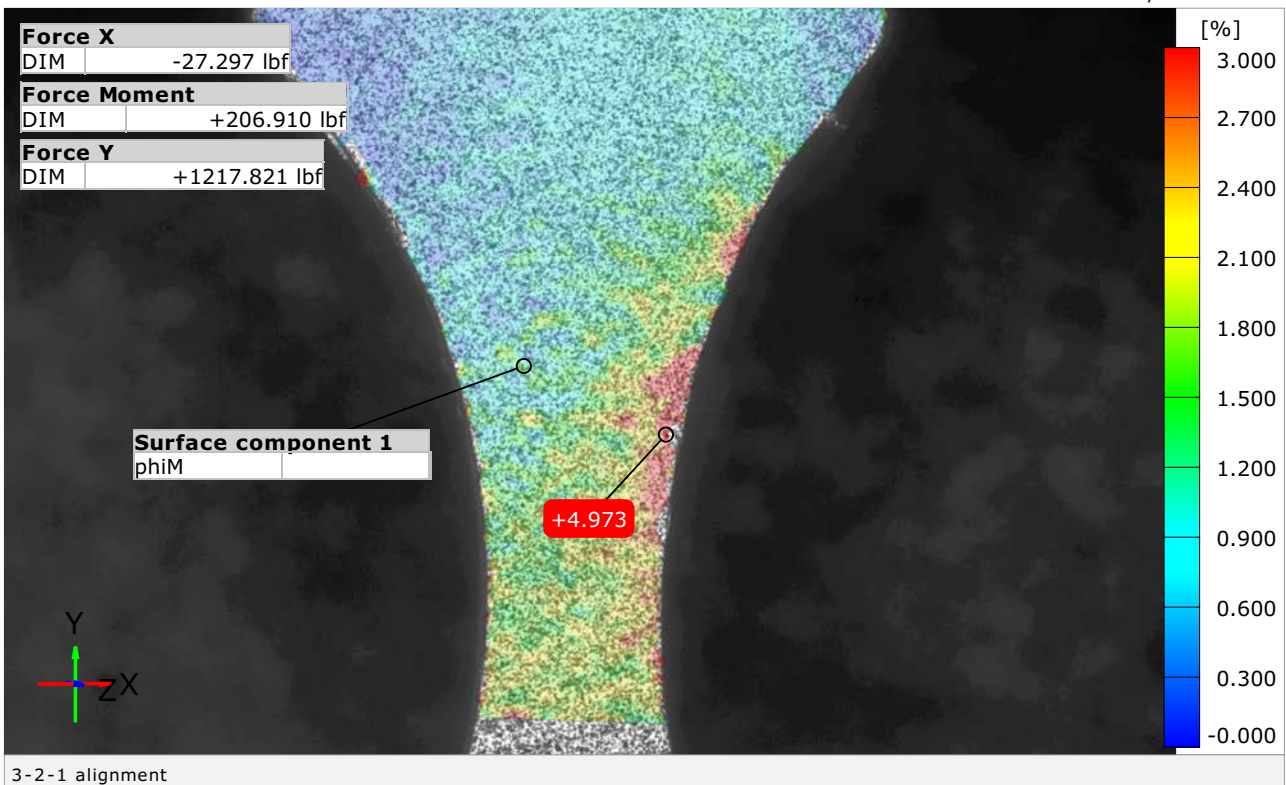
39

Geometry reference: 1



77

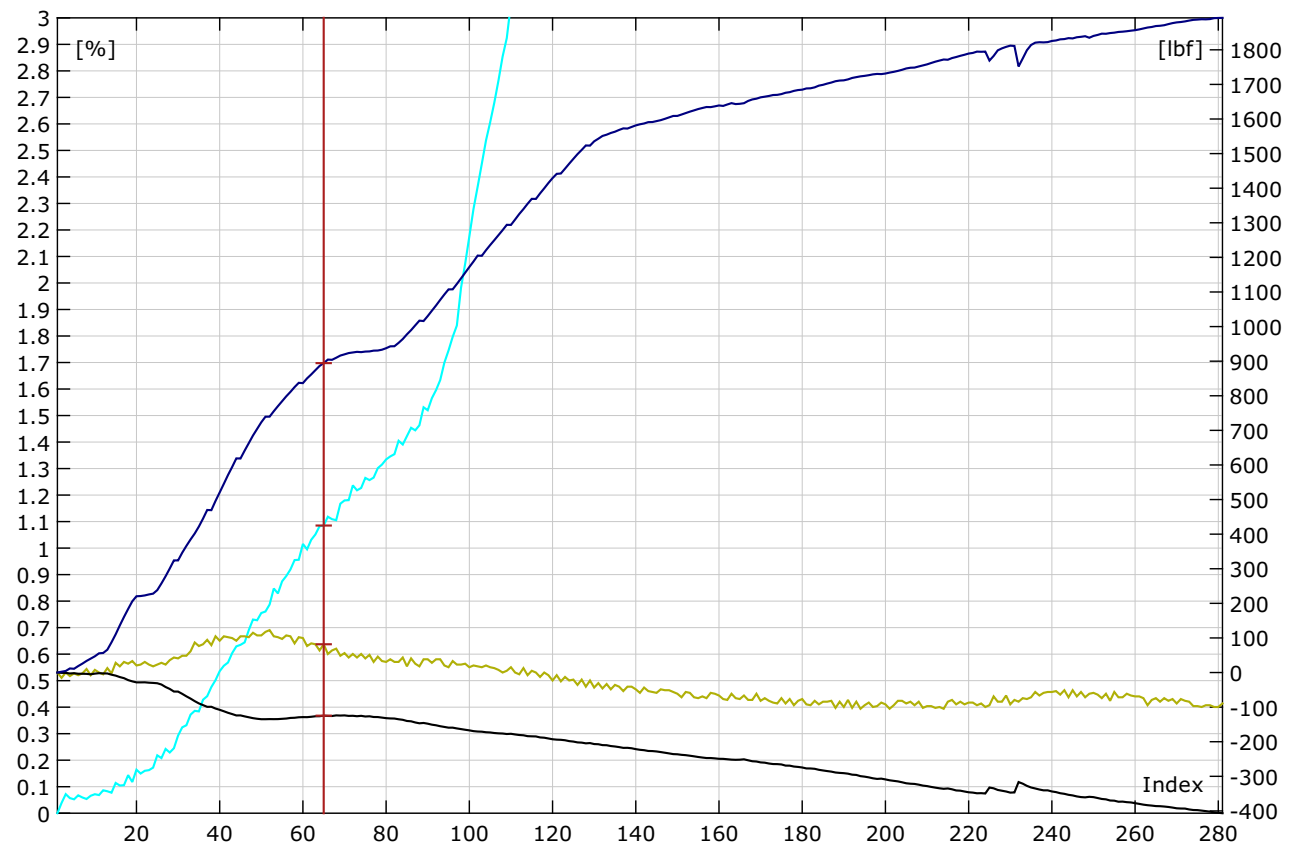
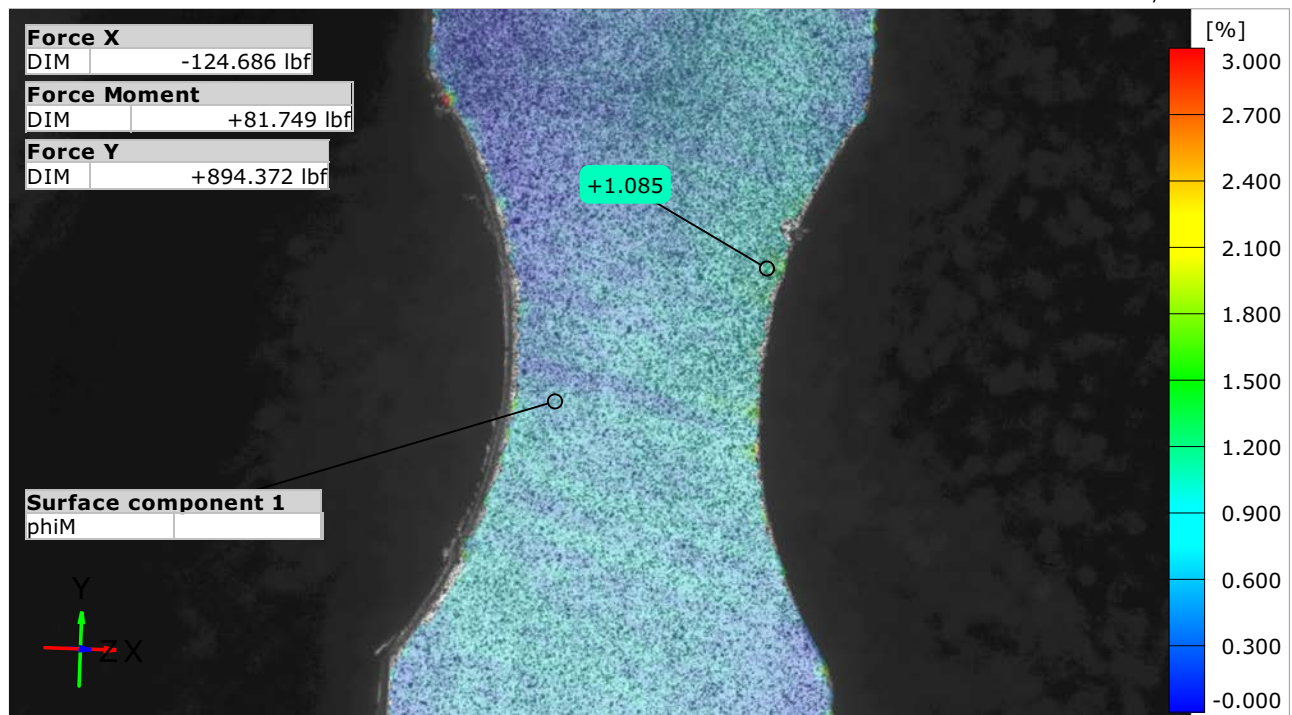
Geometry reference: 1



Triaxial T7 Failure Example (Sample 337)

65

Geometry reference: 1



3-2-1 alignment

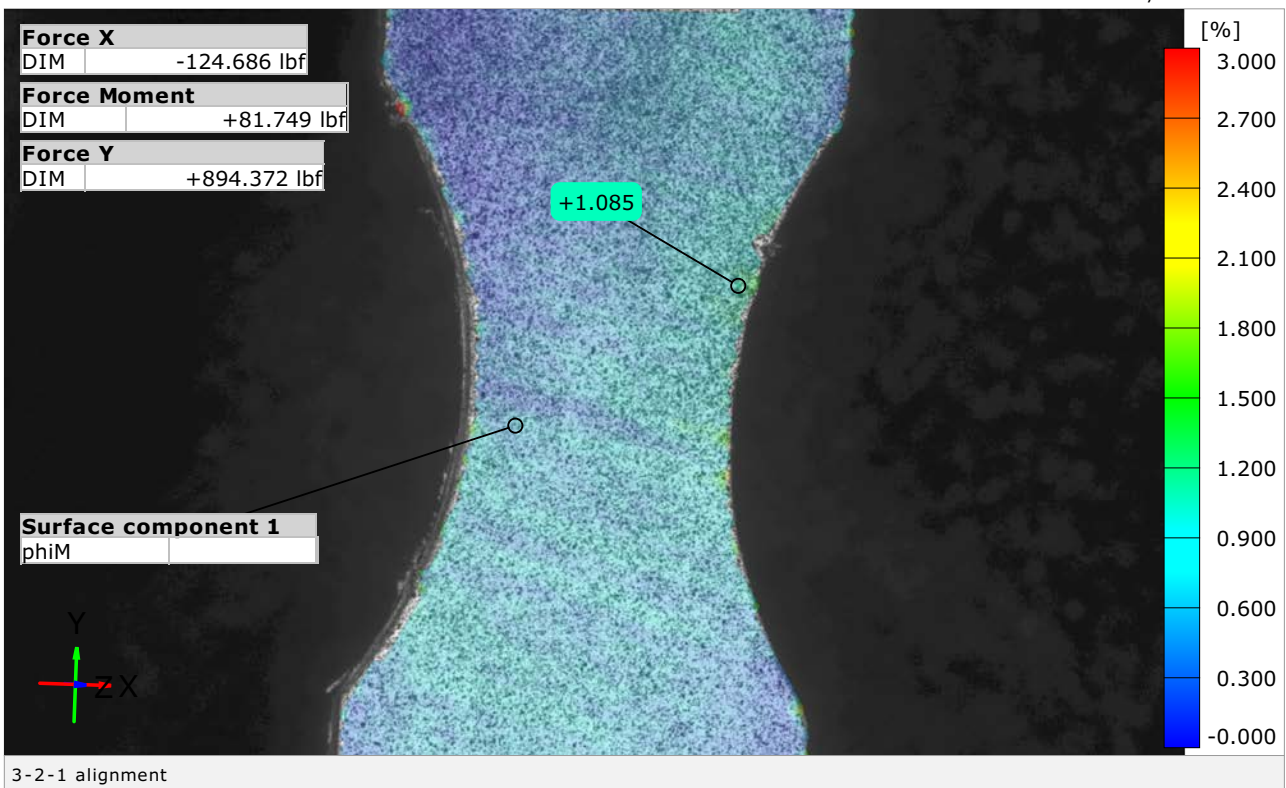
25.07.2024

1/2

Triaxial T7 Further Failure Example (Sample 337)

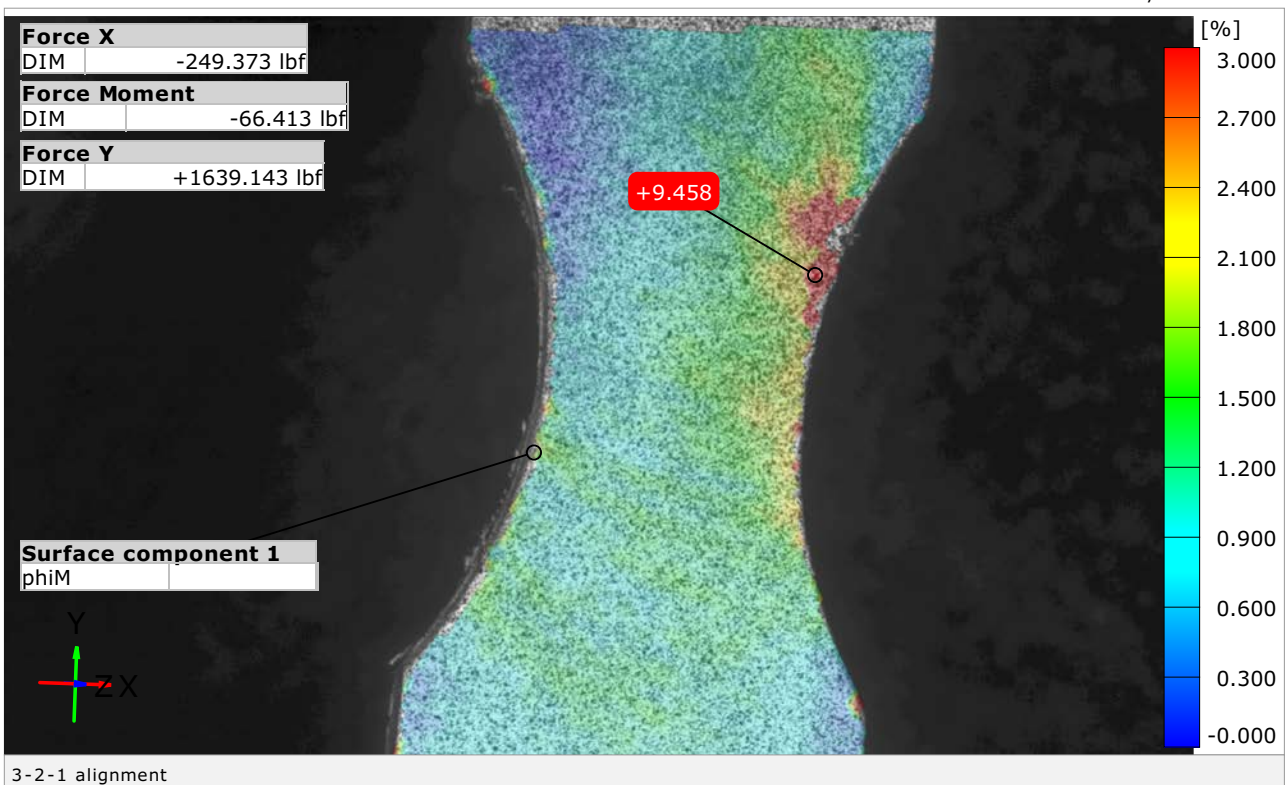
65

Geometry reference: 1



160

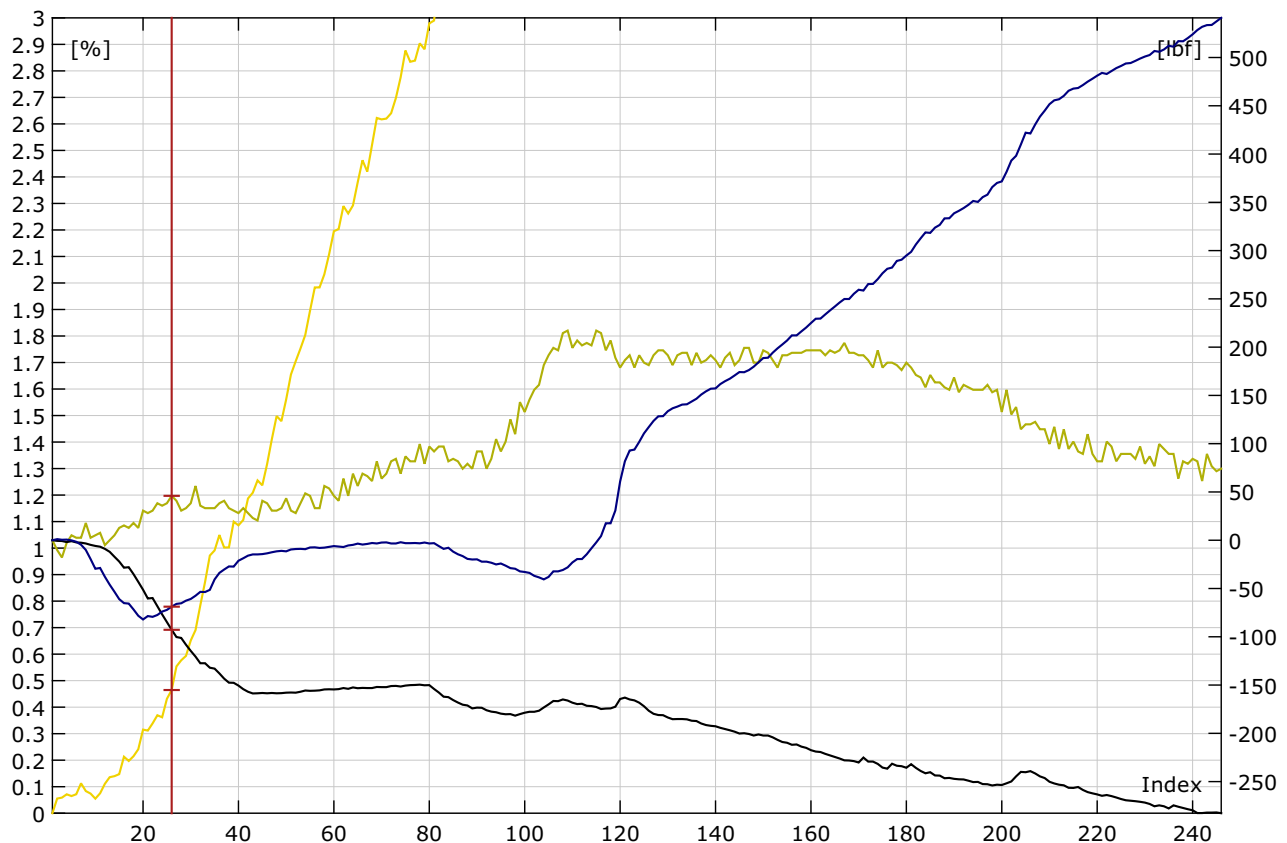
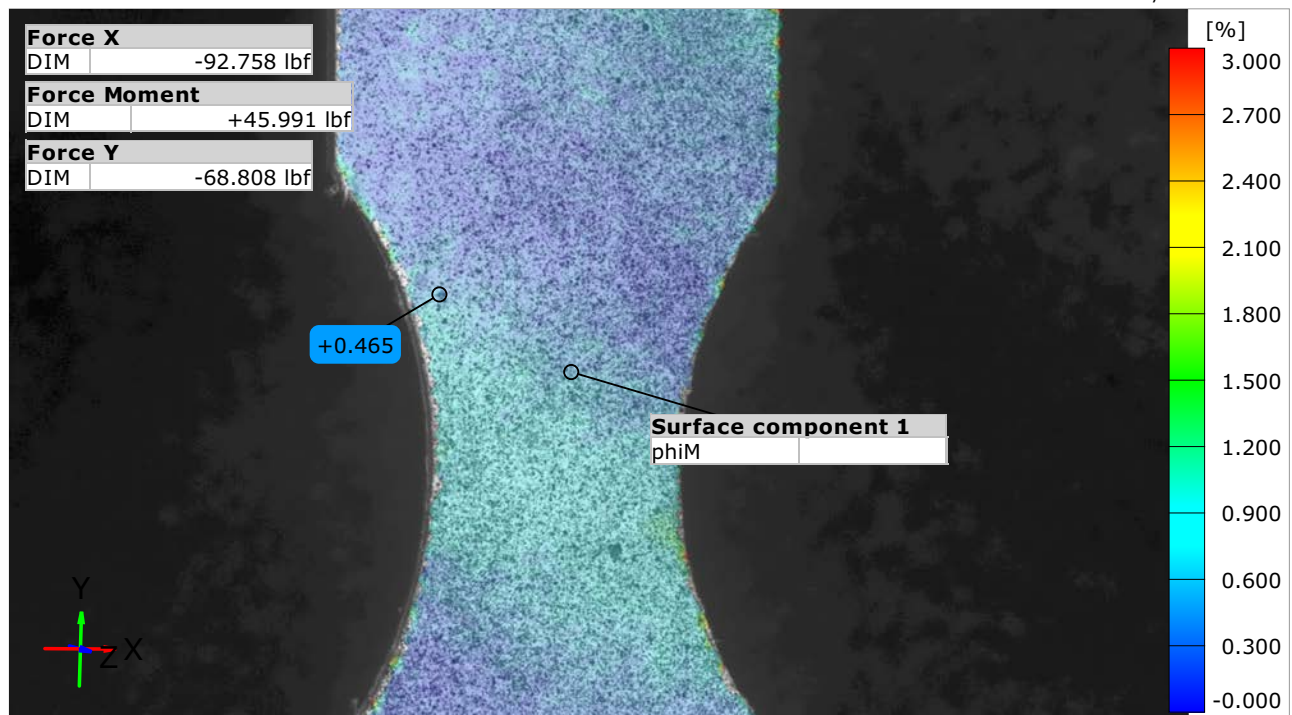
Geometry reference: 1



Triaxial T8 Failure Example (Sample 340)

26

Geometry reference: 1



3-2-1 alignment

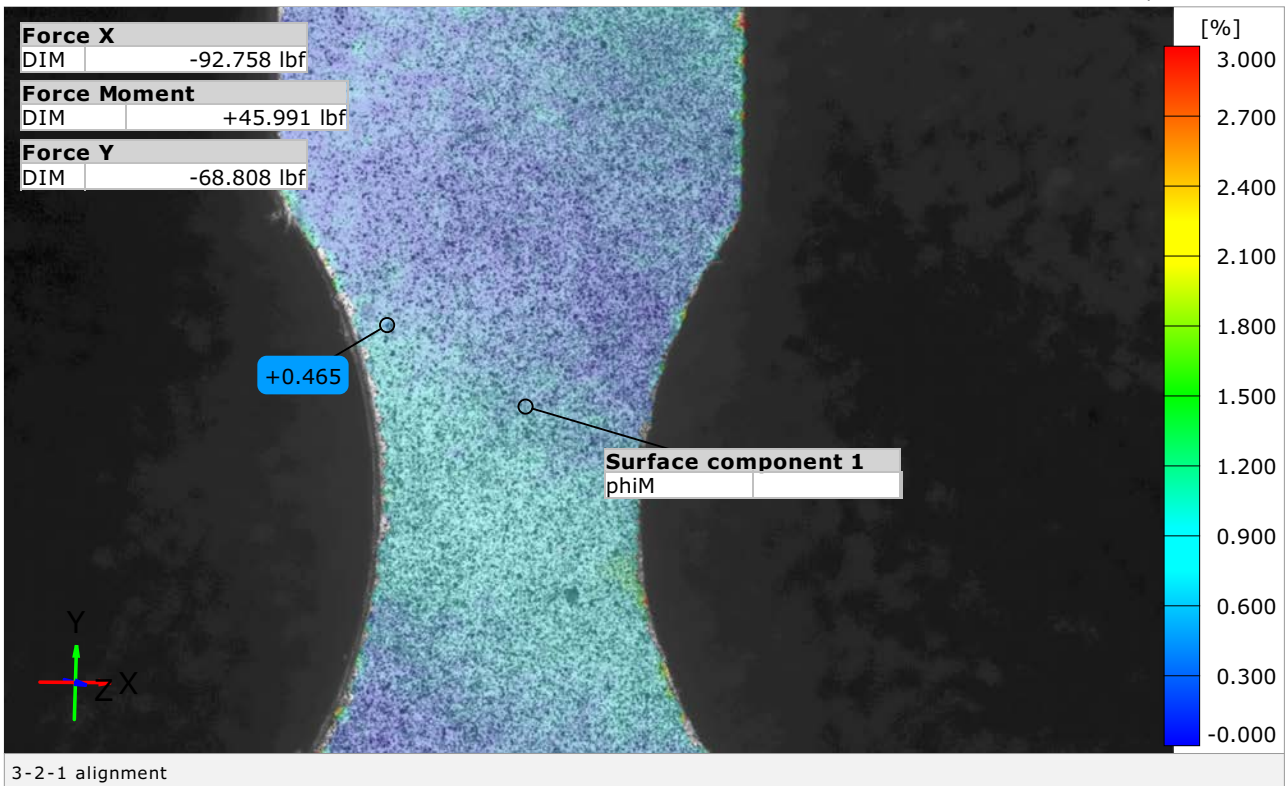
25.07.2024

3/4

Triaxial T8 Further Failure Example (Sample 340)

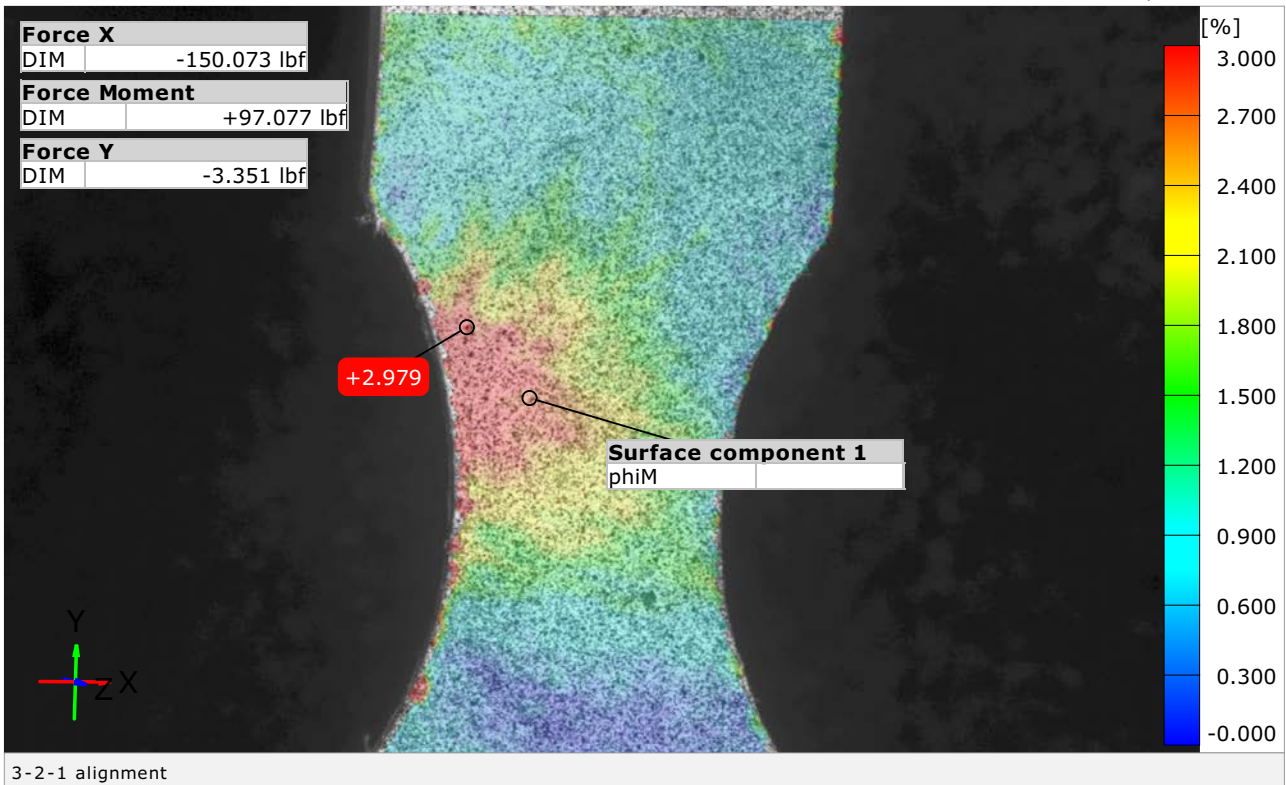
26

Geometry reference: 1



80

Geometry reference: 1



APPENDIX C

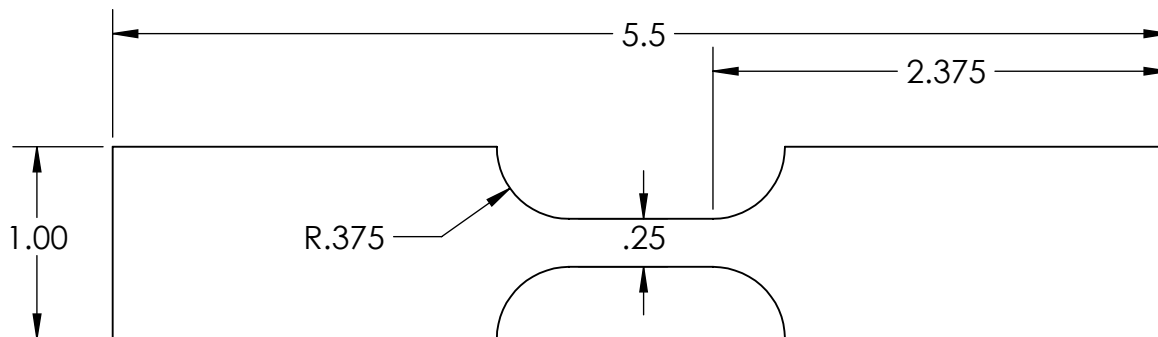
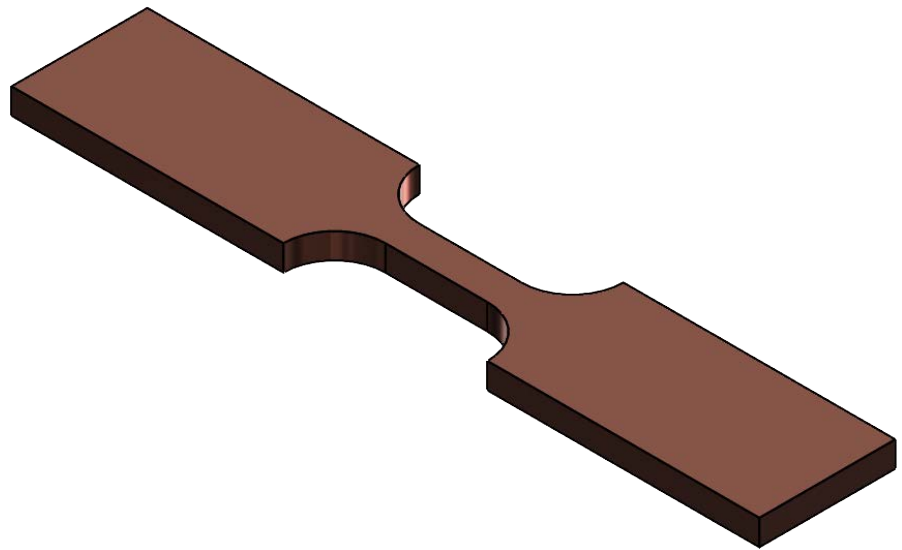
COUPON PART DRAWINGS

2

1

B

B



A

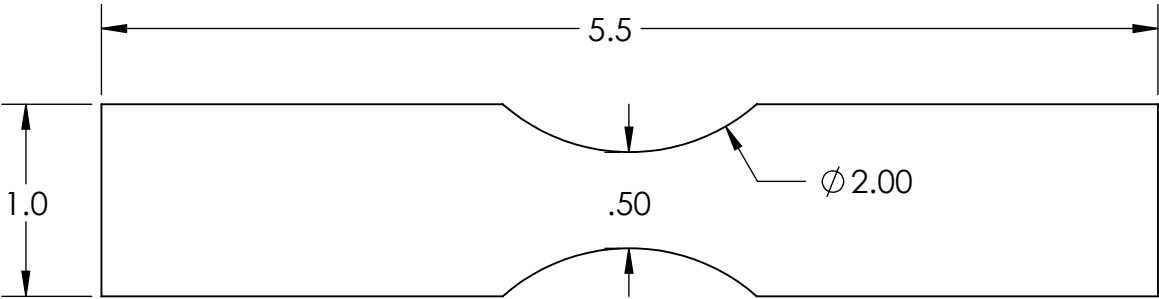
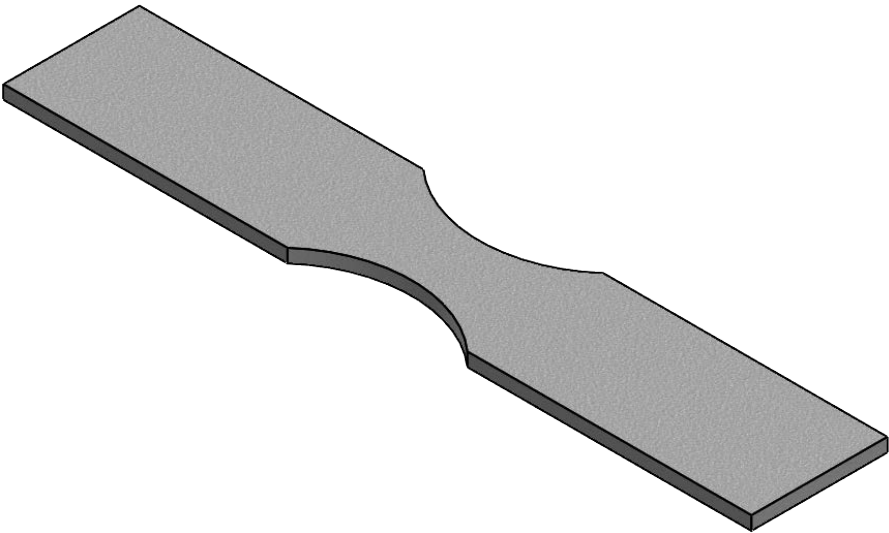
A

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		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL $\pm$ ANGULAR: MACH $\pm$ BEND $\pm$ TWO PLACE DECIMAL $\pm$ THREE PLACE DECIMAL $\pm$		NAME	DATE	Copper Tensile
			DRAWN			
			CHECKED			
			ENG APPR.			
			MFG APPR.			
			Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A
APPLICATION		DO NOT SCALE DRAWING				DWG. NO.
						REV.
						SCALE:1:1
						WEIGHT:
						SHEET 1 OF 1

2

1



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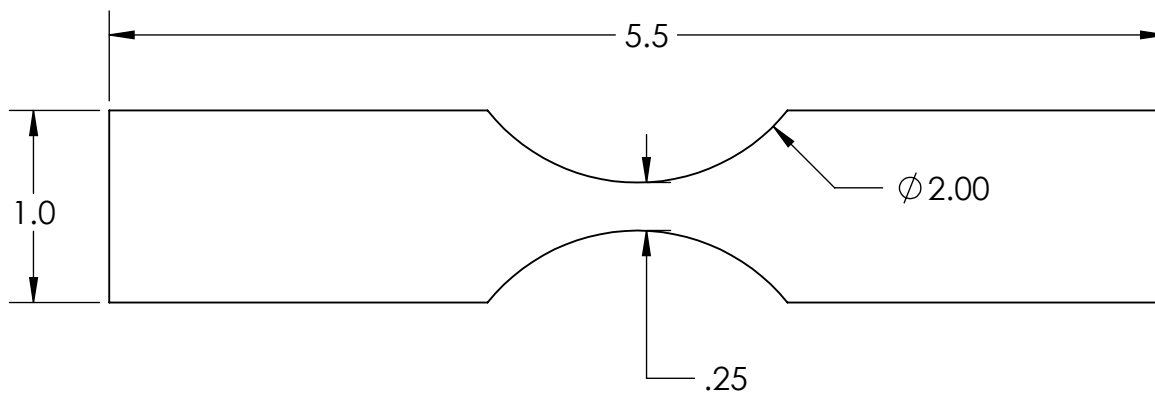
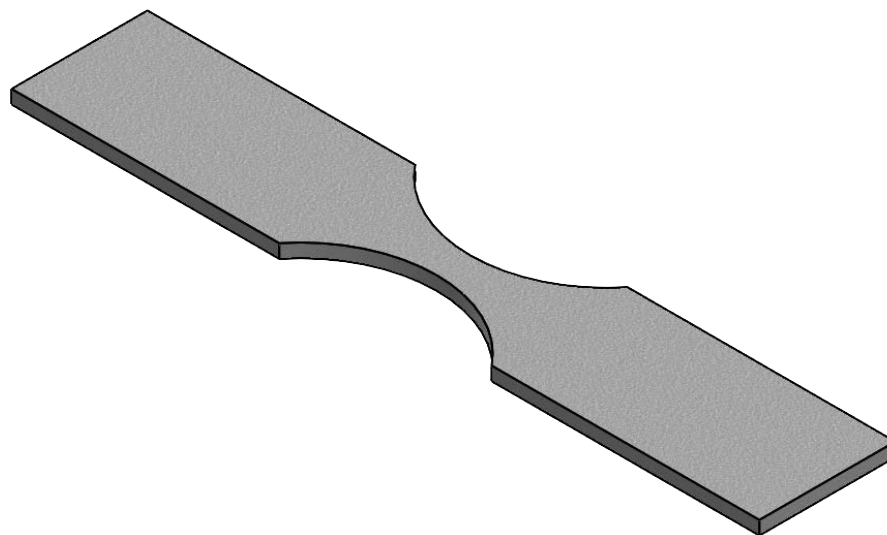
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		NAME	DATE	Fiberglass Bowtie		
				DRAWN				
				CHECKED				
				ENG APPR.				
				MFG APPR.				
		MATERIAL		Q.A.		COMMENTS:		
NEXT ASSY	USED ON	FINISH				SIZE A	DWG. NO.	REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:1	WEIGHT:	SHEET 1 OF 1

2

1

B

B



A

A

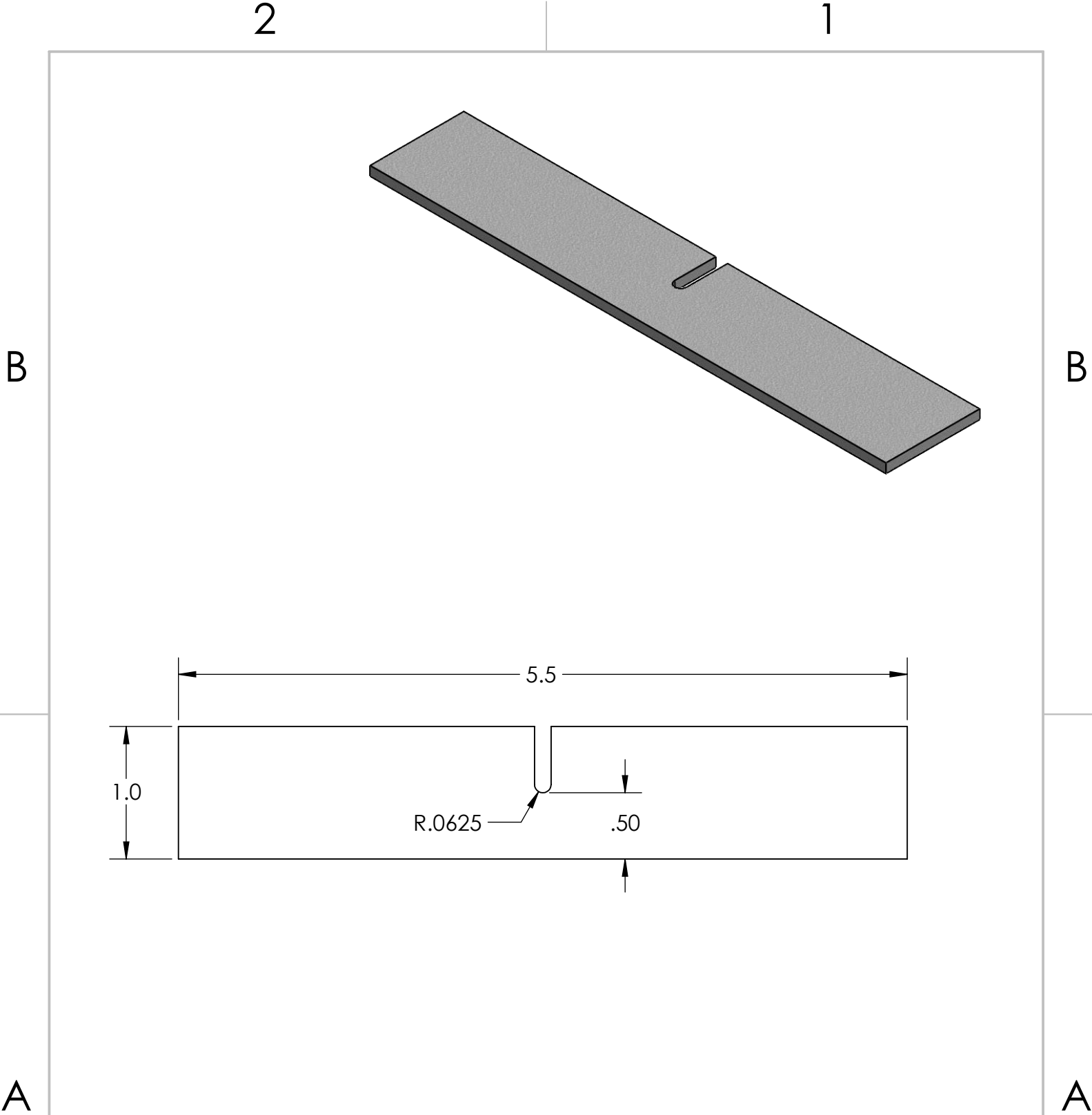
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		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL $\pm$ ANGULAR: MACH $\pm$ BEND $\pm$ TWO PLACE DECIMAL $\pm$ THREE PLACE DECIMAL $\pm$		NAME	DATE	Fiberglass Bowtie			
				DRAWN					
				CHECKED					
				ENG APPR.					
				MFG APPR.					
				Q.A.					
				COMMENTS:					
NEXT ASSY	USED ON	FINISH					SIZE A	DWG. NO.	REV. 1
APPLICATION		DO NOT SCALE DRAWING					SCALE:1:1	WEIGHT:	SHEET 1 OF 1

2

1



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		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±			
		MATERIAL			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

Fiberglass Notch		
SIZE A	DWG. NO.	REV.
SCALE:1:1	WEIGHT:	SHEET 1 OF 1

2

1

APPENDIX D

ARAMIS CODE

This work used the following Aramis code to import forces from analog input readings, apply an equivalent Mises and directional strain across the surface component of a sample, and plot the imported forces on a chart for every test performed. This allowed for consistent analyzation of all tests.

```
# -*- coding: utf-8 -*-

import gom
gom.script.sys.edit_creation_parameters (
    conversion_factor=2224.110808,
    element=gom.app.project.actual_elements ['Analog_input_4'],
    name='Force_X',
    unit='FORCE')

gom.script.sys.edit_creation_parameters (
    conversion_factor=2224.110808,
    element=gom.app.project.actual_elements ['Analog_input_5'],
    name='Force_Y',
    unit='FORCE')

gom.script.sys.edit_creation_parameters (
    conversion_factor=35585.77292,
    element=gom.app.project.actual_elements ['Analog_input_6'],
    name='Force_Moment',
    unit='FORCE')

MCAD_ELEMENT=gom.script.inspection.inspect_dimension (
    elements=[gom.app.project.actual_elements ['Surface_component_1']],
    nominal_value=0.0,
    nominal_value_source='fixed_value',
    properties=gom.Binary (type='mises_strain'))

MCAD_ELEMENT=gom.script.inspection.inspect_dimension (
    elements=[gom.app.project.actual_elements ['Surface_component_1']],
    nominal_value=0.0,
    nominal_value_source='fixed_value',
    properties=gom.Binary (type='epsilon_x'))

MCAD_ELEMENT=gom.script.inspection.inspect_dimension (
    elements=[gom.app.project.actual_elements ['Surface_component_1']],
    nominal_value=0.0,
    nominal_value_source='fixed_value',
    properties=gom.Binary (type='epsilon_y'))

MCAD_ELEMENT=gom.script.inspection.inspect_dimension (
    elements=[gom.app.project.actual_elements ['Surface_component_1']],
```

```
nominal_value=0.0,
nominal_value_source='fixed_value',
properties=gom.Binary (type='epsilon_xy')
```

```
MCAD_ELEMENT=gom.script.inspection.inspect_dimension (
elements=[gom.app.project.actual_elements['Force_X']],
nominal_value=0.0,
nominal_value_source='fixed_value',
properties=gom.Binary (type='dimension')
```

```
MCAD_ELEMENT=gom.script.inspection.inspect_dimension (
elements=[gom.app.project.actual_elements['Force_Y']],
nominal_value=0.0,
nominal_value_source='fixed_value',
properties=gom.Binary (type='dimension')
```

```
MCAD_ELEMENT=gom.script.inspection.inspect_dimension (
elements=[gom.app.project.actual_elements['Force_Moment']],
nominal_value=0.0,
nominal_value_source='fixed_value',
properties=gom.Binary (type='dimension')
```

APPENDIX E

MATLAB CODE

This work used the following MATLAB code to produce 3D scatter plots of the failure points of the composite samples from testing. Each point represents a combination of the strain directions ϵ_{xx} , ϵ_{yy} , and ϵ_{xy} , where the combination of these three values resulted in failure. Testing consisted of various loading directions on samples to get a broader variety of strain combinations that result in failure to plot a greater scope of experienced material failure.

```

%% Excel Strain Failure Plot
%% Joseph Stangl 2024
% Reads excel files and plots the directional strain and forces in 3D
  coordinates
% at moment of failure
%% Clear Database
clc; clear

%% Pull Strains and Forces
samples = 5; % Max number of samples per T direction

% Nomenclature
range    = 'G2:I6'; % Pull strains in all samples and directions
uni_exc  = 'Uniaxial_Tests_Rev_3.xlsx';
bi_exc   = 'Biaxial_Tests_Rev_2.xlsx';
tri_exc  = 'Triaxial_Tests_Rev_3.xlsx';

Uni_Strains = zeros(samples,3,8); % Preallocate
Bi_Strains  = zeros(samples,3,8);
Tri_Strains = zeros(samples,3,8);
SheetNames  = ["T1", "T2", "T3", "T4", "T5", "T6", "T7", "T8"];

% Strain Matrix
for i = 1:8 % Set excel strains to MatLab array
  Uni_Strains(:, :, i) = readmatrix(uni_exc, 'Sheet', ...
  SheetNames(i), 'Range', range);
  Bi_Strains(:, :, i)  = readmatrix(bi_exc, 'Sheet', ...
  SheetNames(i), 'Range', range);
  Tri_Strains(:, :, i) = readmatrix(tri_exc, 'Sheet', ...
  SheetNames(i), 'Range', range);
end

% Force Matrix
range    = 'D2:F6'; % Pull forces in all samples and directions
Uni_Forces = zeros(samples,3,8); % Preallocate
Bi_Forces  = zeros(samples,3,8);
Tri_Forces = zeros(samples,3,8);

for i = 1:8 % Set Excel strains to MatLab array

```

```

Uni_Forces (:,:,i) = readmatrix (uni_exc , 'Sheet' , ...
SheetNames (i) , 'Range' , range);
Bi_Forces (:,:,i) = readmatrix (bi_exc , 'Sheet' , ...
SheetNames (i) , 'Range' , range);
Tri_Forces (:,:,i) = readmatrix (tri_exc , 'Sheet' , ...
SheetNames (i) , 'Range' , range);
end

% Sample Matrix
range = 'A2:A6'; % Pull sample names
Uni_Names = zeros (samples , 1 , 8); % Preallocate
Bi_Names = zeros (samples , 1 , 8);
Tri_Names = zeros (samples , 1 , 8);

for i = 1:8 % Set Excel strains to MatLab array
Uni_Names (:,:,i) = readmatrix (uni_exc , 'Sheet' , ...
SheetNames (i) , 'Range' , range);
Bi_Names (:,:,i) = readmatrix (bi_exc , 'Sheet' , ...
SheetNames (i) , 'Range' , range);
Tri_Names (:,:,i) = readmatrix (tri_exc , 'Sheet' , ...
SheetNames (i) , 'Range' , range);
end

% One Large Matrix
Strain_Matrix = zeros (samples , 3 , 8 , 3); % Preallocate
Strain_Matrix (:,:, :, 1) = Uni_Strains; % Set all strains into one matrix
Strain_Matrix (:,:, :, 2) = Bi_Strains;
Strain_Matrix (:,:, :, 3) = Tri_Strains;

Force_Matrix = zeros (samples , 3 , 8 , 3); % Preallocate
Force_Matrix (:,:, :, 1) = Uni_Forces; % Set all forces into one matrix
Force_Matrix (:,:, :, 2) = Bi_Forces;
Force_Matrix (:,:, :, 3) = Tri_Forces;

Name_Matrix = zeros (samples , 1 , 8 , 3); % Preallocate
Name_Matrix (:,:, :, 1) = Uni_Names; % Set all names into one matrix
Name_Matrix (:,:, :, 2) = Bi_Names;
Name_Matrix (:,:, :, 3) = Tri_Names;

%% Hide Bad Tests
% Uni T7
% disp (Name_Matrix (:, 1 , 7 , 1)) % Row Column T# Layup
Strain_Matrix (:,:, 7 , 1) = [0 0 0;
0 0 0;
0 0 0;

```

```

0 0 0;
0 0 0;];

%% Plot Strains
close all % Close any existing figures
% Ready names and view orientations per subplot
title_index = ["Top Down (Y)", "Isometric", ...
"Top Down (Z)", "Top Down (X)"];
view_index = [0 0; 150 45; 0 90; 270 0]; % 3 view orientations
% Name Tabs
layup_names = ["Uniaxial Strains", "Biaxial Strains", "Triaxial Strains
"];
color_group = [1 0 0; 0 0.8 0; 0 0 1; % Set of colors for T Directions
0.8500 0.3250 0.0980;
1 0 1;
0.9290 0.6940 0.1250;
0.3010 0.7450 0.9330;
0.4660 0.6740 0.1880];

vector_color = gobjects(1, 8); % Preallocate array for legend handles

for l = 1:3 % Per 3 layups
fig = figure('NumberTitle','off', ...
'Name', layup_names(l)); % One figure per layup

fig.Theme = "light"; % White background on figures

% Prepare for Export
set(gcf, 'PaperUnits', 'inches', 'PaperPositionMode', 'auto', ...
'PaperPosition', [0 0 16 16]); % PNG Specs

tiledl = tiledlayout(2,2);
tiledl.Title.String = sprintf(layup_names(l)); % Title figure

for i = 1:4 % Subplot tiles

nexttile(i)

if i == 2
ax = gca; % Get current axes
ax.Visible = 'off'; % Hide tile
nexttile

```

```

end

for j = 1:8 % 8 T directions

for k = 1:5 % 5 seperate sample variables within a column
scatter3(Strain_Matrix(k,1,j,1) ,... % Plot X Y XY strains
Strain_Matrix(k,3,j,1) ,...
Strain_Matrix(k,2,j,1) ,50,color_group(j,:) , 'x')
hold on
xlabel('X_□Strain') % Label axes
ylabel('Y_□Strain')
zlabel('XY_□Strain')
vector = [0, 0, 0; % Vectors from origin
Strain_Matrix(k,1,j,1) ,...
Strain_Matrix(k,3,j,1) ,...
Strain_Matrix(k,2,j,1) ];

% Draw a vector from origin to point
vector_color(j) = plot3(vector(:,1),vector(:,2) ,...
vector(:,3) , 'Color' ,color_group(j,:) , 'LineWidth',1);

end % 3 seperate sample variables within a column

end % 8 T directions

% Axis Identifiers
numround = 0.5; % Round to this number
axismodifier = 1.12; % Add 8% axis length gap to axis label
xaxis = [numround*round(min(min(Strain_Matrix(:,1,: ,1)))/numround)-
numround ...
numround*round(max(max(Strain_Matrix(:,1,: ,1)))/numround)+numround]; %
X bound
yaxis = [numround*round(min(min(Strain_Matrix(:,3,: ,1)))/numround)-
numround ...
numround*round(max(max(Strain_Matrix(:,3,: ,1)))/numround)+numround]; %
Y bound
zaxis = [numround*round(min(min(Strain_Matrix(:,2,: ,1)))/numround)-
numround ...
numround*round(max(max(Strain_Matrix(:,2,: ,1)))/numround)+numround]; %
Z bound
hashmarksx = numround*round(xaxis(1)/numround):numround:xaxis(end); %
Loc of hash
hashmarksy = numround*round(yaxis(1)/numround):numround:yaxis(end);
hashmarksz = numround*round(zaxis(1)/numround):numround:zaxis(end);
hash1 = [-3 3]/60; % Small hash sizes

```

```

hash2 = [-3 3]/25; % Med hash sizes
hash3 = [-3 3]/15; % Large hash sizes
axiscolor = [0 0 0]; % Black axis
axis off; % Turn off default axes
axis_label = ["epsxx (%)","epsyy (%)","epsxy (%)"];

if i == 1 % First subpplot config (Top Down Y)
line(xaxis, [0 0], [0 0], 'Color', axiscolor); % X-axis
line([0 0], [0 0], zaxis, 'Color', axiscolor); % Z-axis
text(xaxis(end)*axismodifier, 0, 0, axis_label(1), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % X label
text(0, 0, zaxis(end)*axismodifier, axis_label(3), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Z label
for a = 1:length(hashmarksx) % X Hashes
line([hashmarksx(a) hashmarksx(a)], [0 0], hash1,...
'Color', axiscolor) % Along X axis
text(hashmarksx(a), 0, -zaxis(end)/15, ...
num2str(hashmarksx(a)), 'Color', axiscolor)
end
for a = 1:length(hashmarksz) % Z Hashes
if hashmarksz(a) ~= 0 % Make exception for 0 on Z axis
line(hash1, [0 0], [hashmarksz(a) hashmarksz(a)],...
'Color', axiscolor) % Along Z axis
text(xaxis(1)/6, 0, hashmarksz(a), ...
num2str(hashmarksz(a)), 'Color', axiscolor)
end
end
lgd = legend(vector_color, SheetNames, ...
'Location', 'none');
lgd.AutoUpdate = 'off';
lgd.Position = [0.75, 0.65, 0.08, 0.26]; % Custom position
lgd.FontWeight = 'bold'; % Make the font bold
lgd.FontSize = 14; % Legend fonts size

elseif i == 3 % Third Subplot Config (Top Down Z)
line(xaxis, [0 0], [0 0], 'Color', axiscolor); % X-axis
line([0 0], yaxis, [0 0], 'Color', axiscolor); % Y-axis
text(xaxis(end)*axismodifier, 0, 0, axis_label(1), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % X label
text(0, yaxis(end)*axismodifier, 0, axis_label(2), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Y label

```

```

for a = 1:length(hashmarksx) % X Hashes
line([hashmarksx(a) hashmarksx(a)], hash1, [0 0],...
'Color', axiscolor) % Along X axis
text(hashmarksx(a), -yaxis(end)/20, 0, ...
num2str(hashmarksx(a)), 'Color', axiscolor)
end

for a = 1:length(hashmarksy) % Y Hashes
if hashmarksy(a) ~= 0 % Make exception for 0 on Y axis
line(hash1, [hashmarksy(a) hashmarksy(a)], [0 0],...
'Color', axiscolor) % Along Y axis
text(xaxis(end)/30, hashmarksy(a), 0, ...
num2str(hashmarksy(a)), 'Color', axiscolor)
end
end

elseif i == 4 % Fourth Subplot Config (Top Down X)
line([0 0], yaxis, [0 0], 'Color', axiscolor); % Y-axis
line([0 0], [0 0], zaxis, 'Color', axiscolor); % Z-axis
text(0, yaxis(end)*axismodifier, 0, axis_label(2), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Y label
text(0, 0, zaxis(end)*axismodifier, axis_label(3), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Z label

for a = 1:length(hashmarksy) % Y Hashes
if hashmarksy(a) ~= 0 % Make exception for 0 on Y axis
line([0 0], [hashmarksy(a) hashmarksy(a)], hash1,...
'Color', axiscolor) % Along Y axis
text(0, hashmarksy(a), zaxis(end)/20, ...
num2str(hashmarksy(a)), 'Color', axiscolor)
end
end

for a = 1:length(hashmarksz) % Z Hashes
line([0 0], hash1, [hashmarksz(a) hashmarksz(a)],...
'Color', axiscolor) % Along Z axis
text(0, yaxis(1)/5, hashmarksz(a), ...
num2str(hashmarksz(a)), 'Color', axiscolor)
end
end

title(title_index(i)) % Tile Plot Title

```

```

% Move Axes Down by Adjusting Y Pos
view(view_index(i,:))

% Reorient Specific Subplots
if i == 2 || i == 4
camup([0 1 0])
end

% title(title_index(i),'Color', axiscolor)
ax = gca;
ax.TitleHorizontalAlignment = 'left';

end % Subplot tiles

% zoom(nexttile(2),2)
fontsize(12,"points")

% Print to update LaTeX
print(layup_names(1),'-dpng','-r600')

end % Per 3 layups

% Move to LaTeX Directory
% Uniaxial
movefile('Uniaxial_Strains.png', ...
'/Users/josephstangl/Documents/Research/Thesis/LaTeX_Thesis_Joseph/figs
')
% Biaxial
movefile('Biaxial_Strains.png', ...
'/Users/josephstangl/Documents/Research/Thesis/LaTeX_Thesis_Joseph/figs
')
% Triaxial
movefile('Triaxial_Strains.png', ...
'/Users/josephstangl/Documents/Research/Thesis/LaTeX_Thesis_Joseph/figs
')

%% Plot Forces
% Ready names and view orientations per subplot
title_index = ["Top Down (Y)","Isometric", ...
"Top Down (Z)","Top Down (X)"];
view_index = [0 0; 150 45; 0 90; 270 0]; % 3 view orientations
% Name Tabs

```

```

layup_names = [" Uniaxial Forces", " Biaxial Forces", " Triaxial Forces"];
color_group = [1 0 0; 0 0.8 0; 0 0 1; % Set of colors for T Directions
0.8500 0.3250 0.0980;
1 0 1;
0.9290 0.6940 0.1250;
0.3010 0.7450 0.9330;
0.4660 0.6740 0.1880];
subp = zeros(1,4); % Preallocate
vector_color = gobjects(1, 8); % Preallocate array for legend handles

for l = 1:3 % Per 3 layups
fig = figure('NumberTitle','off', ...
'Name',layup_names(l)); % One figure per layup

fig.Theme = "light"; % White background on figures

% Prepare for Export
set(gcf,'PaperUnits','inches', 'PaperPositionMode','auto', ...
'PaperPosition', [0 0 16 16]); % PNG Specs

tiledl = tiledlayout(2,2);
tiledl.Title.String = sprintf(layup_names(l)); % Title figure

for i = 1:4 % Subplot tiles

nexttile(i)

if i == 2
ax = gca; % Get current axes
ax.Visible = 'off'; % Hide tile
nexttile
end

for j = 1:8 % 8 T directions

for k = 1:samples % 5 seperate sample variables within a column
scatter3(Force_Matrix(k,1,j,1) ,... % Plot X Y XY strains
Force_Matrix(k,3,j,1) ,...
Force_Matrix(k,2,j,1) ,50,color_group(j,:) , 'x')
hold on
vector = [0, 0, 0; % Vectors from origin
Force_Matrix(k,1,j,1) ,...
Force_Matrix(k,3,j,1) ,...
Force_Matrix(k,2,j,1) ];

```

```

% Draw a vector from origin to point
vector_color(j) = plot3(vector(:,1),vector(:,2),...
vector(:,3),'Color',color_group(j,:), 'LineWidth',1);

end % 3 separate sample variables within a column

end % 8 T directions

% Axis Identifiers
axismodifier = 1.12; % Add 12% axis length gap to axis label
numround = 100; % Round to this number
xaxis = [numround*round(min(min(Force_Matrix(:,1,:),1)))/numround)-
numround ...
numround*round(max(max(Force_Matrix(:,1,:),1)))/numround)+numround]; % X
bound
yaxis = [numround*round(min(min(Force_Matrix(:,3,:),1)))/numround)-
numround ...
numround*round(max(max(Force_Matrix(:,3,:),1)))/numround)+numround]; % Y
bound
zaxis = [numround*round(min(min(Force_Matrix(:,2,:),1)))/numround)-
numround ...
numround*round(max(max(Force_Matrix(:,2,:),1)))/numround)+numround]; % Z
bound
hashmarksx = numround*round(xaxis(1)/numround):numround:xaxis(end); %
Loc of hash
hashmarksy = numround*round(yaxis(1)/numround):numround*2:yaxis(end);
hashmarksz = numround*round(zaxis(1)/numround):numround:zaxis(end);
hash1 = [-3 3]*4; % Small hash sizes
hash2 = [-3 3]*18; % Med hash sizes
hash3 = [-3 3]*25; % Large hash sizes

axiscolor = [0 0 0]; % Black axis
axis off; % Turn off default axes
axis_label = ["Fx (lbf)", "Fy (lbf)", "Fxy (in-lbf)"];

if i == 1 % First subpplot config (Top Down Y)
line(xaxis, [0 0], [0 0], 'Color', axiscolor); % X-axis
line([0 0], [0 0], zaxis, 'Color', axiscolor); % Z-axis
text(xaxis(end)*axismodifier, 0, 0, axis_label(1), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % X label
text(0, 0, zaxis(end)*axismodifier, axis_label(3), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Z label
for a = 1:length(hashmarksx) % X Hashes

```

```

line([hashmarksx(a) hashmarksx(a)], [0 0], hash1,...
'Color', axiscolor) % Along X axis
text(hashmarksx(a), 0, -zaxis(end)/10, ...
num2str(hashmarksx(a)), 'Color', axiscolor)
end
for a = 1:length(hashmarksz) % Z Hashes
if hashmarksz(a) ~= 0 % Make exception for 0 on Z axis
line(hash1, [0 0], [hashmarksz(a) hashmarksz(a)],...
'Color', axiscolor) % Along Z axis
text(xaxis(1)/4, 0, hashmarksz(a), ...
num2str(hashmarksz(a)), 'Color', axiscolor)
end
end
lgd = legend(vector_color, SheetNames,...
'Location', 'none');
lgd.AutoUpdate = 'off';
lgd.Position = [0.75, 0.65, 0.08, 0.26]; % Custom position
lgd.FontWeight = 'bold'; % Make the font bold
lgd.FontSize = 14; % Legend fonts size

elseif i == 3 % Third Subplot Config (Top Down Z)
line(xaxis, [0 0], [0 0], 'Color', axiscolor); % X-axis
line([0 0], yaxis, [0 0], 'Color', axiscolor); % Y-axis
text(xaxis(end)*axismodifier, 0, 0, axis_label(1), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % X label
text(0, yaxis(end)*axismodifier, 0, axis_label(2), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Y label

for a = 1:length(hashmarksx) % X Hashes
line([hashmarksx(a) hashmarksx(a)], hash2, [0 0],...
'Color', axiscolor) % Along X axis
text(hashmarksx(a), -yaxis(end)/15, 0, ...
num2str(hashmarksx(a)), 'Color', axiscolor)
end

for a = 1:length(hashmarksy) % Y Hashes
if hashmarksy(a) ~= 0 % Make exception for 0 on Y axis
line(hash1, [hashmarksy(a) hashmarksy(a)], [0 0],...
'Color', axiscolor) % Along Y axis
text(xaxis(end)/20, hashmarksy(a), 0, ...
num2str(hashmarksy(a)), 'Color', axiscolor)
end
end

```

```

elseif i == 4 % Fourth Subplot Config (Top Down X)
line([0 0], yaxis, [0 0], 'Color', axiscolor); % Y-axis
line([0 0], [0 0], zaxis, 'Color', axiscolor); % Z-axis
text(0, yaxis(end)*axismodifier, 0, axis_label(2), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Y label
text(0, 0, zaxis(end)*axismodifier, axis_label(3), ...
'HorizontalAlignment', 'left', ...
'Color', axiscolor); % Z label

for a = 1:length(hashmarksy) % Y Hashes
if hashmarksy(a) ~= 0 % Make exception for 0 on Y axis
line([0 0], [hashmarksy(a) hashmarksy(a)], hash1,...
'Color', axiscolor) % Along Y axis
text(0, hashmarksy(a), zaxis(end)/20, ...
num2str(hashmarksy(a)), 'Color', axiscolor)
end
end

for a = 1:length(hashmarksz) % Z Hashes
line([0 0], hash2, [hashmarksz(a) hashmarksz(a)], ...
'Color', axiscolor) % Along Z axis
text(0, yaxis(1)/5, hashmarksz(a), ...
num2str(hashmarksz(a)), 'Color', axiscolor)
end
end

title(title_index(i)) % Tile Plot Title

% Move Axes Down by Adjusting Y Pos
view(view_index(i,:))

% Reorient Specific Subplots
if i == 2 || i == 4
camup([0 1 0])
end

% title(title_index(i), 'Color', axiscolor)
ax = gca;
ax.TitleHorizontalAlignment = 'left';
end % Subplot tiles

% zoom(nexttile(2), 1.75) % Zoom in on the isometric subplot
fontsize(12, "points")

```

```

% Print to update LaTeX
print(layup_names(l), '-dpng', '-r600')

end % Per 3 layups

% Move to LaTeX Directory
% Uniaxial
movefile('Uniaxial_Forces.png', ...
'/Users/josephstangl/Documents/Research/Thesis/LaTeX/Thesis_Joseph/figs
')
% Biaxial
movefile('Biaxial_Forces.png', ...
'/Users/josephstangl/Documents/Research/Thesis/LaTeX/Thesis_Joseph/figs
')
% Triaxial
movefile('Triaxial_Forces.png', ...
'/Users/josephstangl/Documents/Research/Thesis/LaTeX/Thesis_Joseph/figs
')

```