Environmental Control System (ECS) Ducting Design Guide

Raytheon, Stratasys, Air Force Research Labs

Design Guide

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1. Introduction and Background

1.1 Scope

This technical design guide describes the design, processing, manufacture, and post-processing techniques and procedures for additive manufactured environmental control system (ECS) ducting using Stratasys FDM® (fused deposition modeling) technology. The principles discussed and requirements provided in this guide for part creation and implementation should be followed whenever possible. Due to various industry best-practices, deviations to this design guide may be implemented at the discretion of the individual user's expertise.

1.2 Application Overview

ECS ducting, relative to both automotive and aerospace, supplies temperature-controlled air to crew and passengers to regulate cabin temperature and promote airflow throughout the cabin. ECS ducts are typically low pressure (below 15 psi [1.03 bar]), thin-walled, lightweight, with no exposure to harsh temperatures or chemicals. The FDM process and materials allow for a cost-effective method for producing ECS ducting geometries within these requirements for low volume and complex ducts.

1.3 Background and Purpose

Currently ECS ducts are made out of aluminum, flexible fabric hoses, composite lay-ups and rotationally molded thermoplastics. Traditional manufacturing methods for complex geometries or low volumes can be costly, with long lead times, and regularly require assembly after production to achieve the desired geometry.

The FDM process performs well with both complex geometries and in low-volume duct manufacturing. Many aircraft and automotive components, such as ECS ducts, fit with one or both of these scenarios. FDM ducting offers an economic way to produce ducts for low volume production runs, ducts featuring a high level of geometric complexity, or prototype aircraft and automobiles with multiple design revisions required.

Figure 1: Ducts, in limited production runs and customized shapes, can be produced at a lower cost compared to traditional manufacturing methods.

2. Design Overview

2.1 Design Guide Objectives

This design guide provides best practices for the manufacture of FDM ECS ducting. It provides design-for-additive-manufacturing (DFAM) techniques, sealing procedures, and test data to demonstrate the ability of FDM ducts to meet industry requirements for use in production applications.

This guide includes:

- Key properties and characteristics for relevant materials
- Advantages and considerations for FDM ducting
- Best practices in duct design
- Best practices in file preparation, processing, and fabrication
- Best practices in post-processing/duct sealing
- Leak and burst characterization data

2.2 Design Guide Approach

The design guide details experiments performed on different Insight™* seam conditions, sealing methods, and toolpath algorithms. The experiments determined:

- Ideal ducting settings
- Workflow to optimize duct strength
- Sealing with minimal post-processing
- Data for FDM ECS ducting in aircraft and automobiles

(*Insight is the pre-processing software that imports the .stl file and exports the .cmb file that controls the 3D printer.)

3. FDM Material

The primary material focus in this guide is ULTEM™ 9085 resin, a flame retardant, high performance thermoplastic for manufacturing. It is ideal for ECS ducting with its high strength-to-weight ratio and FST (flame, smoke, and toxicity) rating.

3.1 Key Material Design Considerations

3.1.1 Thermal

Ducting applications should remain under the heat deflection temperature of the material (307 °F [153 °C]) in order to ensure dimensional stability of the duct.

3.1.2 Pressure

The leak testing in this design guide was performed up to 15 psi (1.03 bar), detailed in Section 7.1, since this value covers the majority of ECS ducting applications.

Burst-proof testing supports extended operation at a minimum of 50 psi, as detailed in Section 7.3. The testing verified that ducts, designed using the methods detailed in this design guide, perform well in high-pressure applications.

3.1.3 Anticipated Life

Life cycle estimation utilized pressure and thermal cycling testing on two-contour ULTEM 9085 ducts. Ducts subjected to 10,000 pressurization/depressurization cycles showed no adverse effects. The test data shown in Figure 2 shows a trend line with a slight improvement in leak rate, though statistically negligible.

Ducts subjected to 250 thermal cycles, from -65 °F to +160 °F (-54 °C to +76 °C), displayed no measurable, adverse effects in leak rate. These are not exhaustive qualification tests; however, they give reasonable assurance that a moderate number of pressure and thermal cycles do not materially degrade the leak performance of ULTEM 9085 resin ducts.

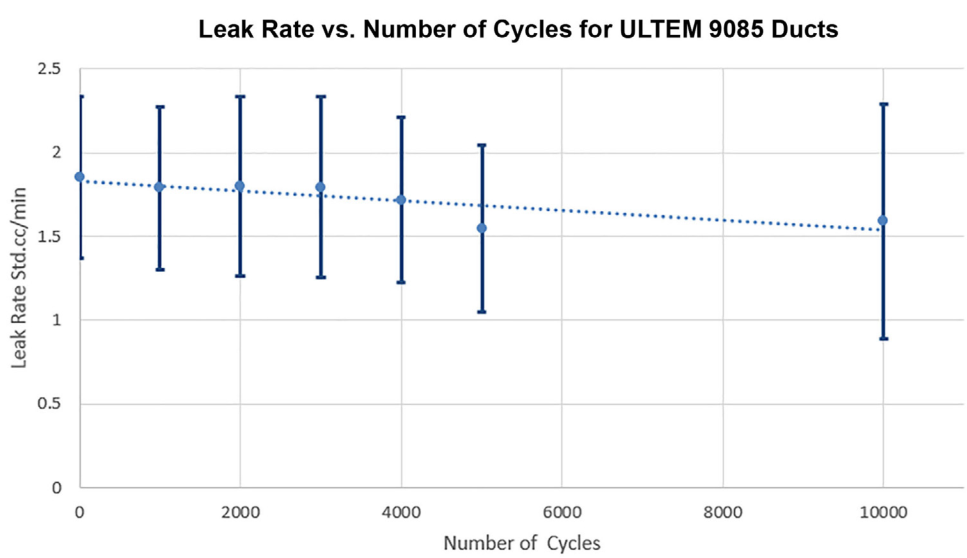


Figure 2: No degradation in leak rate after 10,000 pressure cycles.

4. Duct Design and Construction Considerations

This section describes the unique design considerations when designing duct geometries. They are not meant to cover basic DFAM considerations when designing for all FDM parts.

4.1 Minimum Wall Thickness

The wall thickness of FDM ducting is limited by the toolpath thicknesses of material deposited during the FDM process. Two toolpaths of material must fit within the wall of the duct to process and build properly. The default bead width for the 0.010 inch (0.254 mm) slice height is 0.020 inch (0.508 mm). Therefore, the minimum wall thickness for a duct at this slice height is 0.040 inch (1.016 mm). Figure 3 shows a minimum wall thickness duct and the toolpaths to fill this geometry.

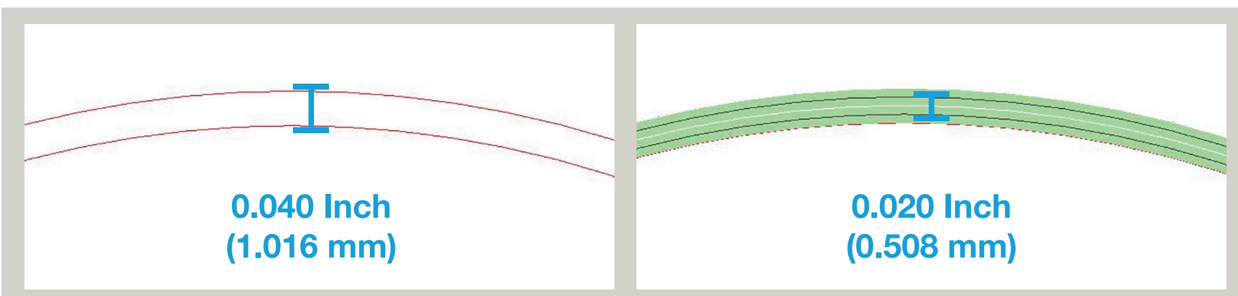


Figure 3: The minimum recommended wall thickness for FDM ducting (left) in order to properly fill the geometry with the standard toolpaths (right).

The testing detailed in this design guide focuses on the 0.010 inch (0.254 mm) slice height. It is the recommended slice height for building FDM ducting:

- Providing a good combination of build speed and feature resolution.
- Utilizing smaller toolpath thicknesses to minimize weight.

A larger slice height, 0.013 inch (0.3302 mm), is possible with ULTEM 9085 resin. The same design rules apply with this slice height, but the increased toolpath thickness must account for minimum wall thicknesses when using this slice height.

4.2 Overhang Angles

FDM has the unique capability to produce parts with overhang angles of less than 45 degrees from vertical, without needing support material (Figure 4). This self-supporting angle reduces material usage, build time, and post-processing of the duct.

The self-supporting angle is especially important when designing FDM ducting. Support material trapped inside complex tubes makes it difficult or impossible to remove after the part's production.

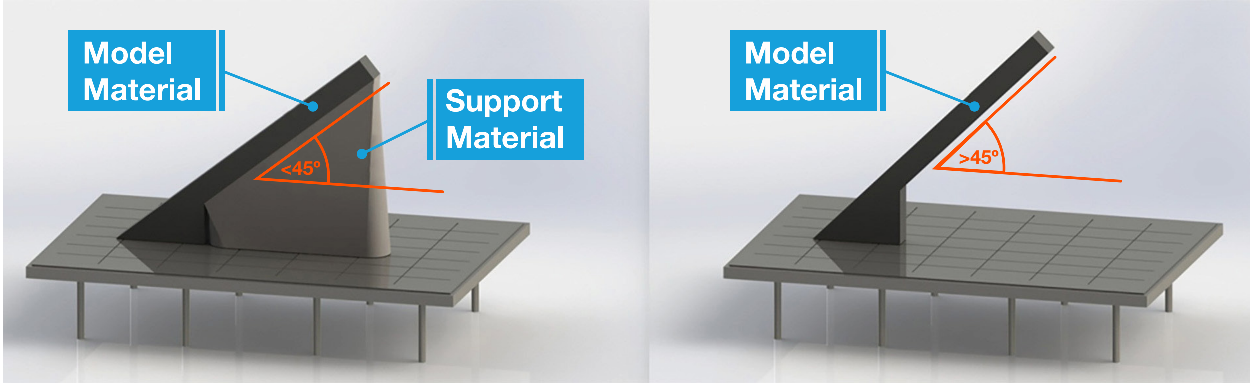


Figure 4: An angle less than 45 degrees from the build plane needing support (left) and an angle greater than 45 degrees not requiring support material (right).

Always utilize the self-supporting angle when producing FDM ducting to prevent or reduce trapped support material within the duct. This normally results in a vertical build orientation as shown in Figure 5.

Keeping the duct vertical in the build chamber and reducing sharp changes in direction also promotes sealing (see Section 7.1). If it is not possible to produce the duct without support material inside (which is often the case), ensure there are access points to remove the support or change the build orientation.

Figure 5: Vertical build orientations promote sealing, improve surface finish, and reduce the amount of support material needed.

4.3 Variable Cross-Sections/Remnant Fill

Slicing a three-dimensional object into two-dimensional slice curves presents a unique challenge for producing thin-walled geometries with FDM.

A duct of constant wall thickness in three-dimensional space, sliced at an angle, produces two-dimensional curves with a variable cross-sectional thickness as shown in Figure 6. The variation of the two-dimensional slice depends on the severity of the angle from vertical. The more severe the angle, the larger the variation.

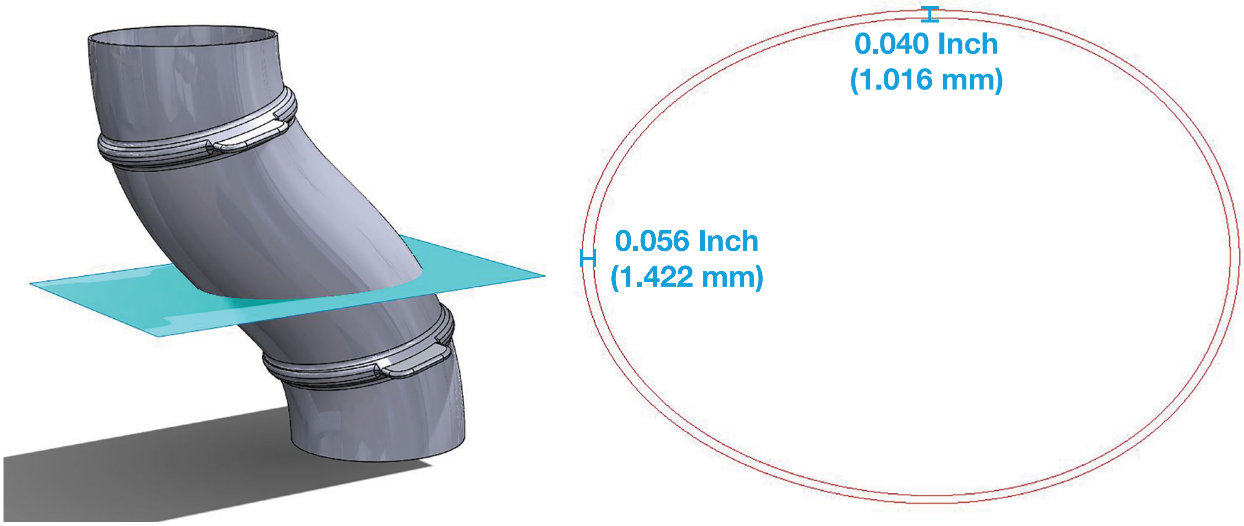


Figure 6: A duct with a constant 0.040 inch (1.016 mm) wall thickness yields a varying cross-sectional thickness (right) when sliced into two-dimensional curves in angled areas of the duct, as indicated by the blue plane (left).

Filling these variable cross-section curves on thin walled parts has traditionally been difficult. Thicker geometries fill the area in between the curves with rasters (Figure 7), addressing variation.

Constant-thickness, thin-walled cross sections can be filled by changing the contour width using a custom group (see the FDM Best Practice Document: Custom Groups in Insight). Variable cross sections that are too thin to be filled with rasters create voiding between the contours shown in Figure 7. These voids compromise structural integrity and allow for a potential leak path through the part.

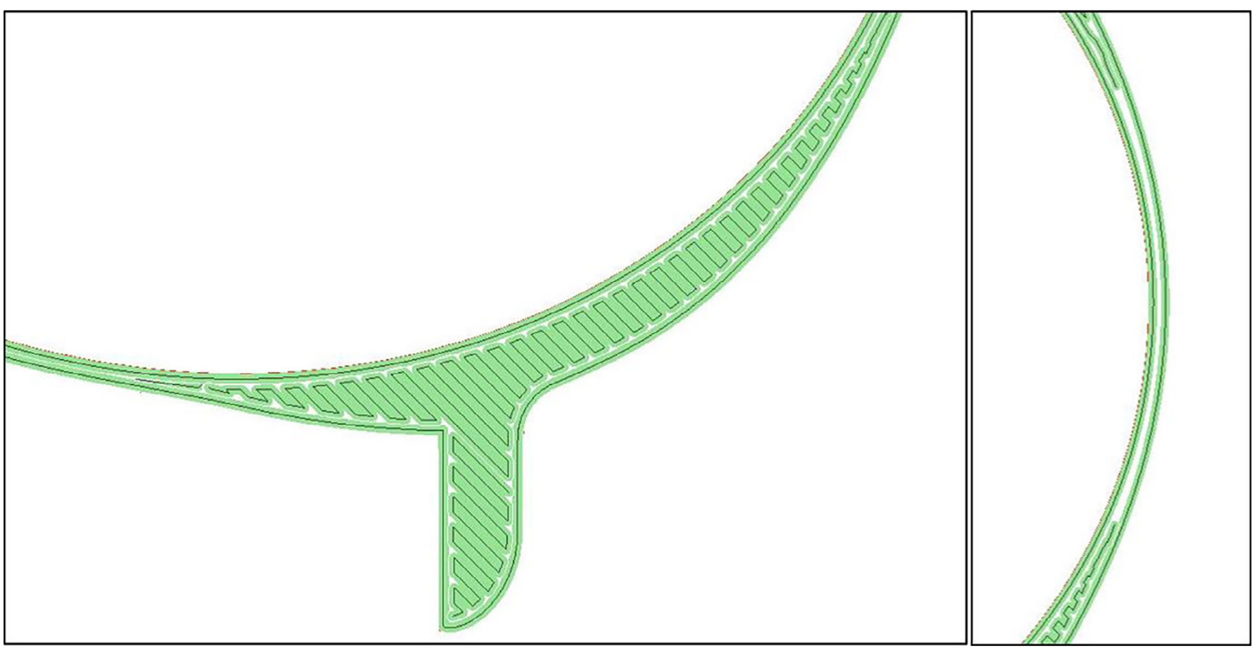


Figure 7: Thick parts with variation are filled by rasters (left) but thin, variable cross-sections cause voiding between the inner and outer contour (right).

A new fill algorithm called remnant fill, used in FDM ducting and other thin walled applications, detects areas not filled by contours or rasters. The algorithm extrudes a variable width toolpath to fill the void (Figure 8). This algorithm is available for the Fortus 900mc™ and F900™ Printers starting in Insight 12.4, build 6115, and Section 5.2.1 describes enabling this feature. Remnant fill for the Fortus 450mc™ is in development and will be supported in later releases of the software.

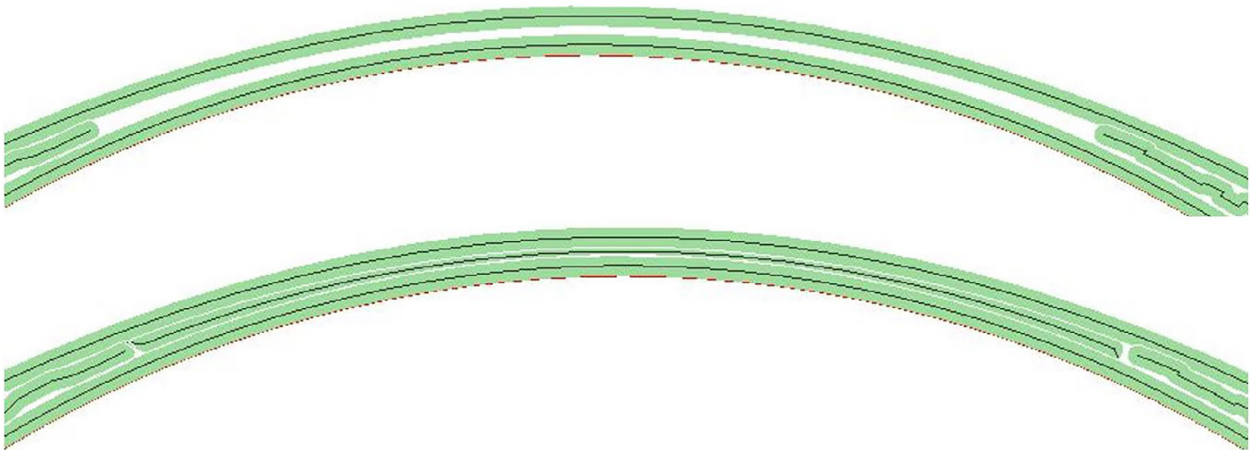


Figure 8: The standard fill algorithm left voids in areas between contours that were too thin for rasters (top). Remnant fill detects these voids and fills them with a variable-width toolpath (bottom).

Remnant fill provides better crush strength (see Section 7.4) and promotes sealing of ducting (see Section 7.1.4) compared to a standard-fill algorithm.

4.4 Bifurcations

Bifurcations or other junctions are capable of being added to a single duct geometry. Additive manufacturing allows for easily produced junctions, reducing overall part count. Apply self-supporting angles to ensure support removal from the inside of the duct. These junction points tend to lead to support generation (Figure 9).

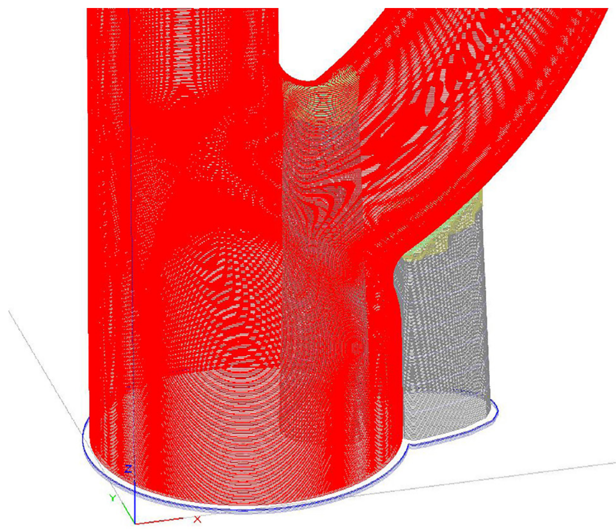


Figure 9: A bifurcated duct (red) with support material (grey and gold) to support the branching section of the duct with easy access to remove the internal support through the bottom of the duct.

4.5 Integrated Mounting Features

To reduce assembly time and part count, incorporate mounting features and consolidate multiple ducts into a single part. Figure 10 shows a duct with mounting feet, as well as a cable-routing bracket integrated into a single-part duct design. It's an effective alternative to welding multiple parts.

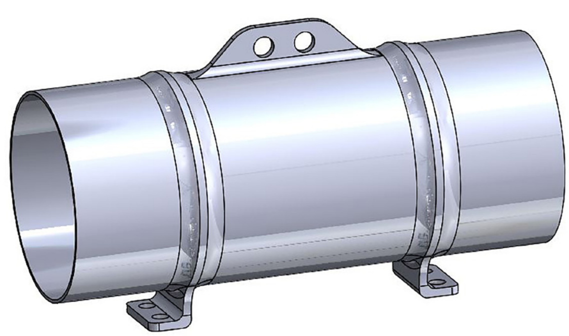


Figure 10: Additive manufacturing allows for integrated features and part consolidation.

5. Insight Processing

Insight is the pre-processing software that imports the .stl file and exports the .cmb file controlling the 3D printer. Insight designates material, machine and slice-height selections, combined with build orientation and toolpath parameters, to control the duct build.

The following sections assume a basic knowledge of Insight software. See the Step-By-Step Insight Processing Procedure Best Practice document for Insight assistance. If outsourcing the production of parts, designating processing parameters for the build orientation, slice height and desired material in engineering drawings ensure ducts are processed and produced by the service provider correctly.

5.1 Build Orientation

As mentioned in previous sections, a vertical build orientation (Figure 11) improves surface finish, reduces support material, and promotes sealing.

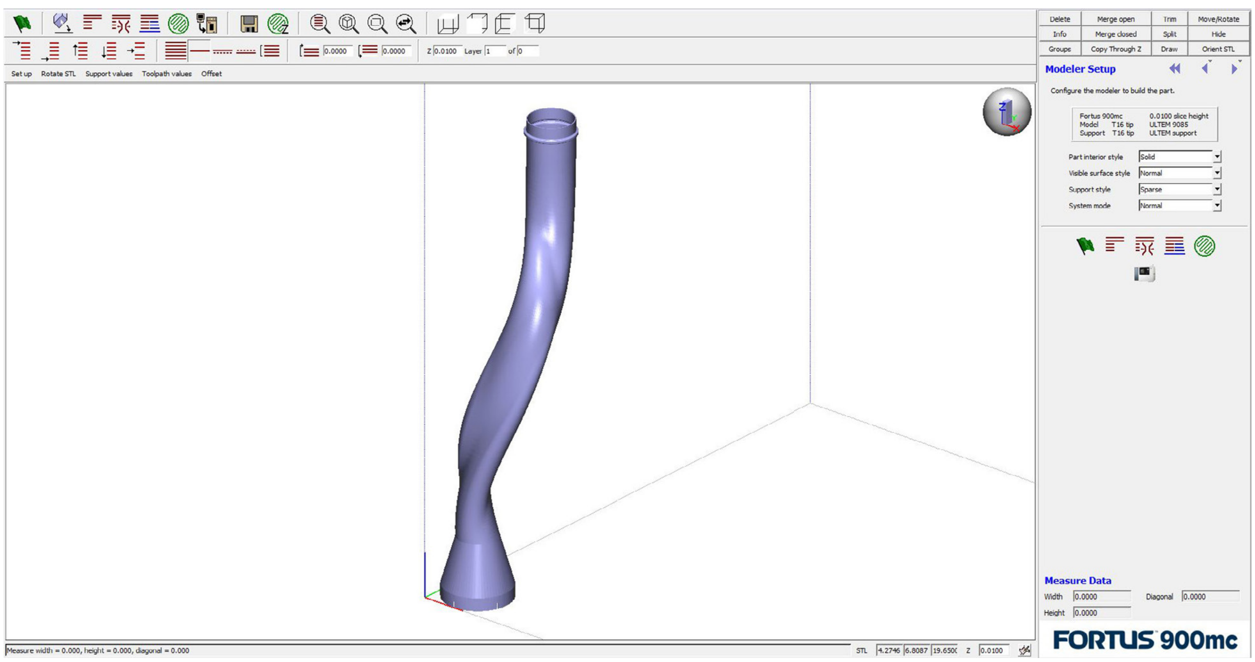


Figure 11: A wide variety of build orientations are possible depending on part geometry but typically a vertical orientation produces the best duct.

Insight allows multiple manipulations of the part's build orientation once imported. A facet of the part can be selected to be either the top, bottom, left, right, front, or back of the build using the **Orient by selected facet** option under the **STL** tab of the menu bar, shown in Figure 12. Select one of the options from the menu and then click the desired facet to render this orientation. For example, select the bottom option and then click the face of the part to be the bottom of the build (Figure 12).

The part can also be rotated relative to its original imported orientation or relative to its current orientation by entering in rotation angle values under the **Rotate** option within the **STL** tab of the menu bar (Figure 13). The rotation about X, Y, and Z boxes controls the global rotation values of the part relative to its imported orientation. The green rotation arrows at the bottom of the menu can be used to rotate the part relative to its current position by the angle entered into the rotation increment box.

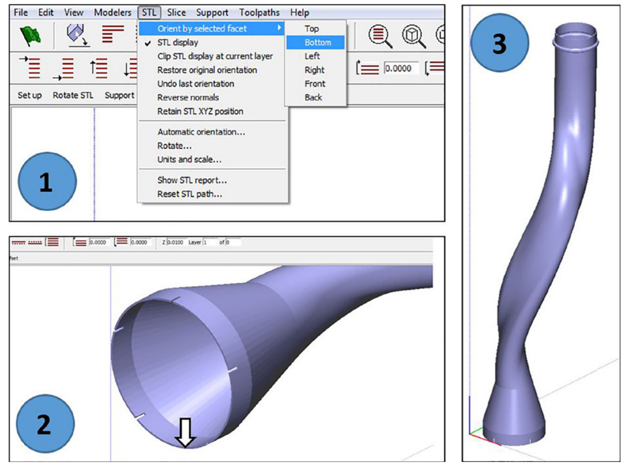


Figure 12: In this example, selecting "bottom" (1), and then selecting the flat end of the duct (2) makes this face the bottom of the part in the build envelope (3).

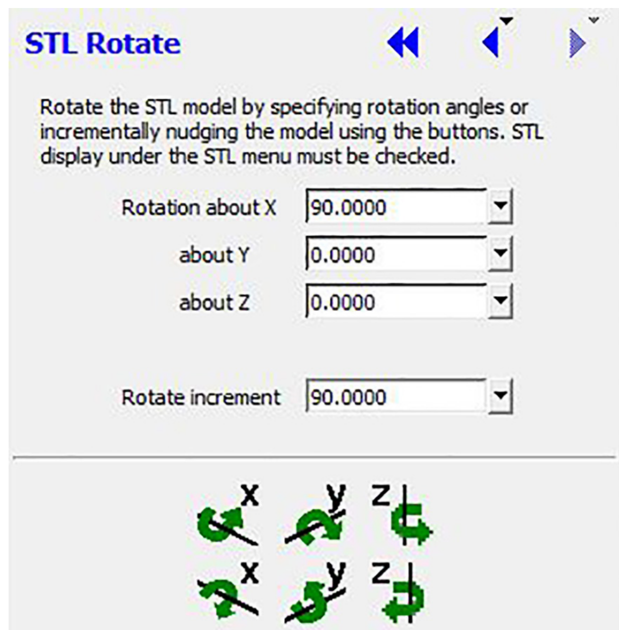


Figure 13: Using the STL Rotate menu is another option for tailoring the orientation of the part.

5.2 Toolpath Considerations

Insight offers several advanced control options for customizing the toolpath generation of parts. It is recommended to use default values for all parameters not detailed in this section unless the user is significantly advanced in Insight and has determined that the changed values produce better results for a specific geometry.

5.2.1 Remnant Fill

As mentioned in the previous section, remnant fill is currently available for the Fortus 900mc and F900 Printers. To use this feature, Insight must be upgraded to version 12.4, build 6115 or greater and the machine software must be upgraded to 3.27.0 or greater. The remnant fill feature can be accessed from the **Toolpaths > Setup** option by clicking the radio button icon to enter the advanced toolpath parameters menu (Figure 15). The remnant fill algorithm will then automatically detect and fill the previously voided regions.

5.2.2 Linked Contours

Seams are one of the major features contributing to FDM part pressure leakage. Seams are created when the machine starts and stops each contour of a part. The standard setting dictates that there is a seam for each individual contour, generally in the same place around the circumference of the part. Linking these contours is possible by enabling the linked contour feature tying two adjacent contours at the seam as shown in Figure 14. The link contours feature can be accessed from the **Toolpaths > Setup** option and clicking the radio button icon to enter the advanced toolpath parameters menu (Figure 15). For a thin duct with a wall thickness of two contours, the inner and outer contours automatically link together during toolpath generation when the linked contour feature is enabled. Thicker ducts should use at least two contours around the outside and inside of the duct, when possible, employing the linked contour feature. Linking contours helps to eliminate the flow path at the seam and improves sealing of the duct (see Section 7.1.2 for test data).

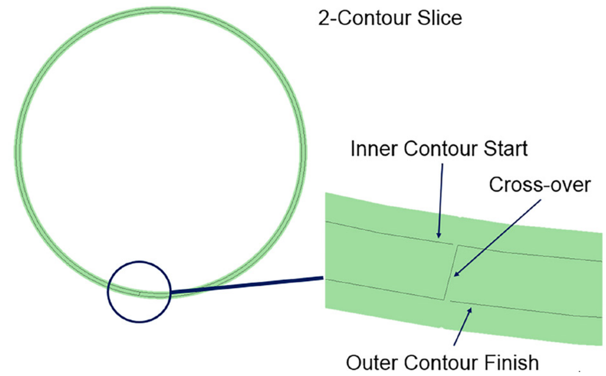


Figure 14: A continuous toolpath reduces porosity at the seams.

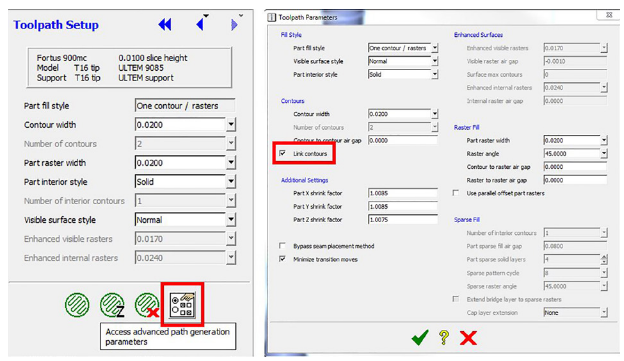


Figure 15: Enabling remnant fill and linking contours can be done through the advanced toolpath settings.

5.2.3 Offset Rasters

While linked contours promote sealing in the X-Y build direction, the offset rasters feature can aid Z-direction sealing in sections of the duct that require rasters. This feature offsets the rasters of each subsequent layer by half a toolpath width, placing the center of the toolpath of the above layer at the previous layer's raster joint (Figure 16), reducing the ability for air to flow between rasters. An extra contour added to the offset layer fills the space left by the missing half raster on each edge. The offset rasters feature can be accessed from the **Toolpaths > Setup** option, clicking on the radio button icon to enter the advanced toolpath parameters menu (Figure 17).

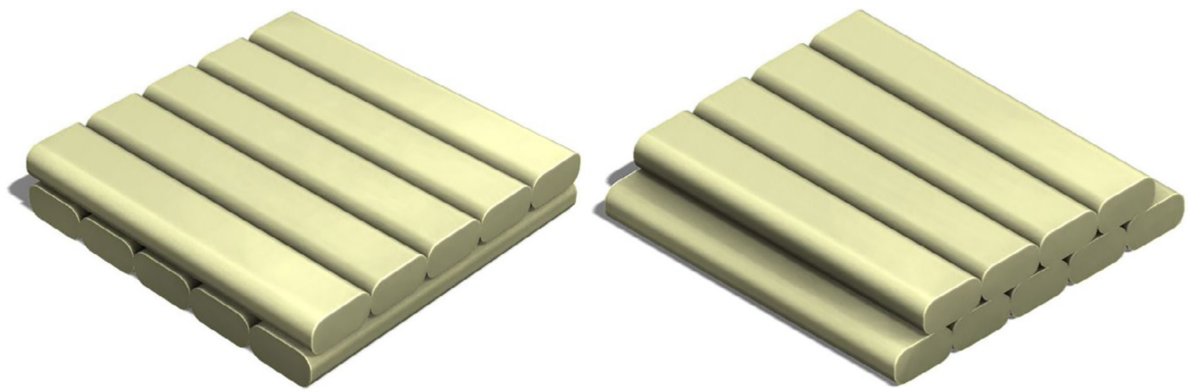


Figure 16: Default rasters generated at a 45-degree angle within the build plane and alternate ± 45-degrees each layer (left). Offset rasters shift by half a toolpath width every layer, rather than rotate, to promote inter-layer sealing (right).

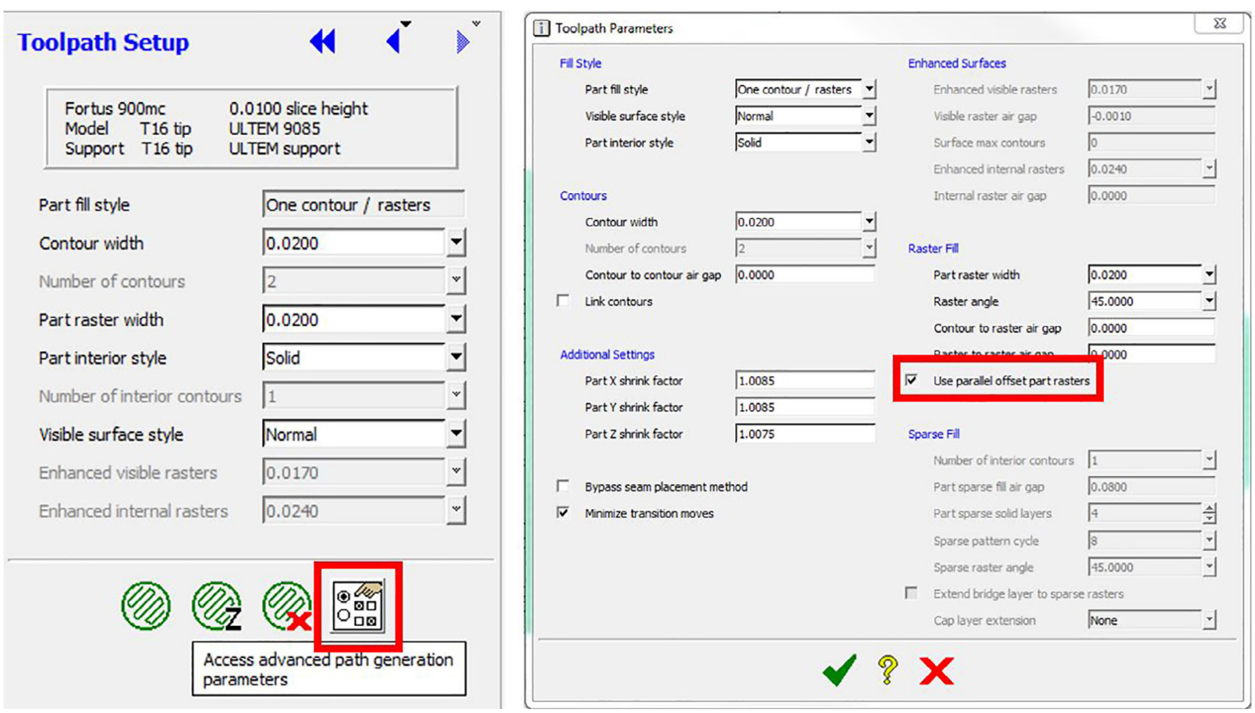


Figure 17: The offset rasters feature is under the advanced toolpath menu, the same menu as the link contours feature.

Note that the offset rasters feature does not alternate raster direction by default. Achieve better orthotropic properties by manually alternating the raster direction a minimum of every three layers using the **Delta angle** control in a custom group (Figure 18). Keeping a minimum of three layers between angle changes allows for offset toolpaths to fill inter-layer porosity.

5.2.4 Seam Control

As mentioned in previous sections, a seam is the start/stop point of a contour. Linking the seams of multiple contours together promotes sealing, as does aligning the seams on top of one another, per layer, in the vertical direction. Insight allows for multiple seam control options: **automatic**, **automatic back facing**, **align**, **align to nearest**, **random**, and **random back facing**. They are all accessed through the **Toolpaths > Seam control** menu and selected from the dropdown box (Figure 19).

- Automatic: Uses the default algorithm to attempt to distribute the seams on edges to minimize the visual appearance of the seams.
- Automatic back facing: Performs the same seam placement as automatic, but attempts to place the seams on the back of the part (the face of the part furthest in the +Y direction).
- Align: Performs seam placement based on user input and places the seam as close to the user dictated point as possible for each given curve.
- Align to nearest: Aligns seams closest to a user-dictated point, but the seam must be located on a vertex (aligning to the nearest vertex from the dictated point). For the cube example: If the user-dictated point was in the middle of a face, **align** would place the seam in the middle of the face, but **align to nearest** would place the seam at the edge of the cube (the nearest vertex to the dictated point).
- Random: Randomizes the seam placement throughout the part
- Random back facing: Randomizes seam placement, but attempts to place seams on the back of the part (the section of the part furthest in the +Y direction).

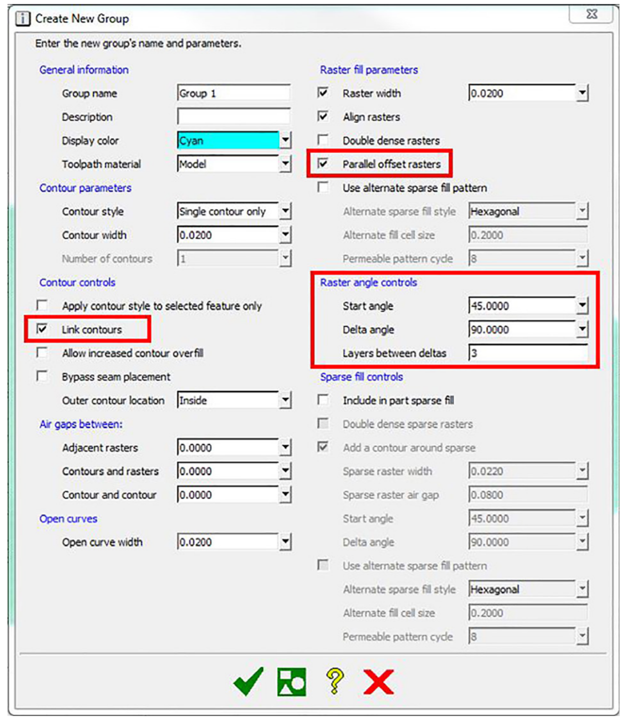


Figure 18: Raster angle controls. Check the link contours and the offset raster boxes within the custom group menu.

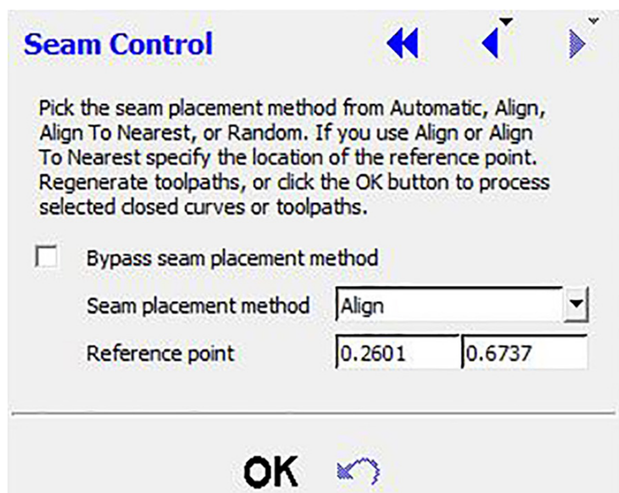


Figure 19: The seam control menu allows for customization of the starts/stops of contours within a part.

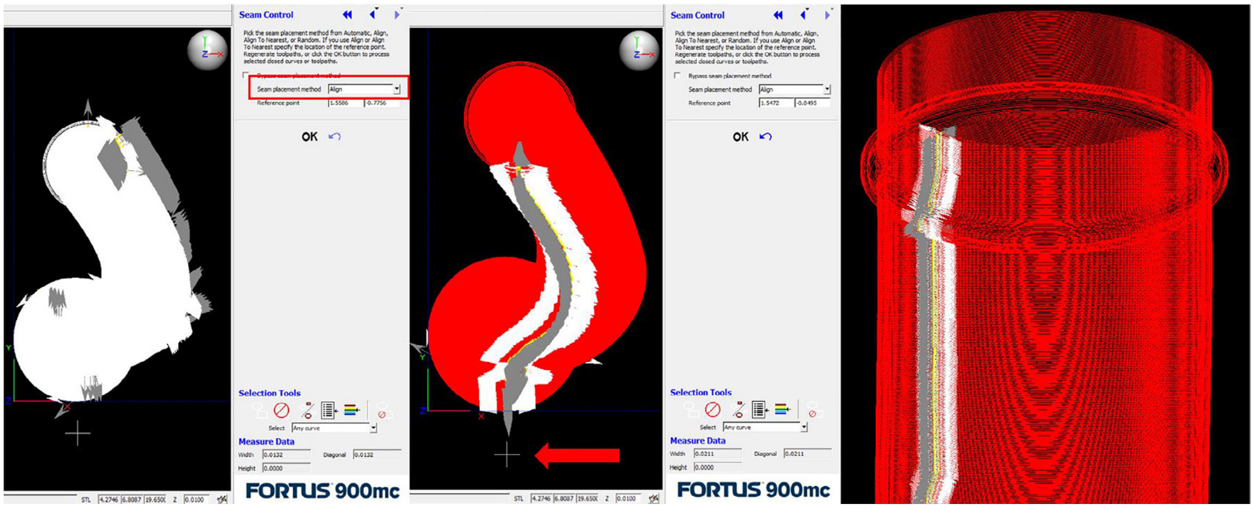


Figure 20: The align seam control method is selected from the dropdown box and the layers to align seams are selected (left). The user dictates a point to align the seams closest to the white cross pointed to by the red arrow (center). The final result of an aligned seam is indicated by a yellow point and a white arrow pointing in the toolpath direction (right).

For ducting applications, use the align seam control method. This ensures that the seams will directly stack on top of one another, promoting sealing (see Section 7.1.2 for test data on different seam conditions). Testing has shown that the majority of leaking happens at the seam. Aligning the seam in a single continuous line also allows for easier post-process sealing methods, in contrast to randomized seams. Figure 20 displays an example of aligning seams for a part and an aligned part seam is shown in Figure 21.

Figure 21: Seam control plays an important role in leak reduction.

5.3 Support Generation

ULTEM 9085 resin uses a breakaway support material only. It is strongly recommended to reduce or eliminate internal supports within a duct since the support material must be removed by hand. Consider this during the design process and avoid designs where support will be trapped in deep cavities, holes or inaccessible interior parts of the duct. Minimizing the amount of support will also reduce the build time of the part. Breakaway support removal is aided by default support parameters (sparse for ULTEM 9085 resin); therefore, default support settings are recommended when generating supports for ducting applications.

5.3.1 Stabilizer walls

A duct is typically a high aspect ratio part, with a vertical orientation being the ideal build direction, leading to a tall part with a small footprint on the build sheet in the XY plane. Tall parts such as these often require additional support to prevent vibration or collapse during the build. Stabilizer walls are single-bead structures that slightly penetrate into the part to help stabilize it during building, shown in Figure 22. The stabilizing structures are easily removable after the build owing to their perforations, similar to a perforated piece of paper. Stabilizer walls can be accessed through the **Support > Stabilize** wall menu.

A top-down view of a stabilizer wall and specific design details are shown in Figure 23. Leave parameters not detailed as default.

- The **Separation** value controls how far the back of the wall separates from the part.
- The **Contact interval** value controls how much distance is between each contact leg of the stabilizer wall.
- The **Penetration** value controls how deep the wall penetrates into the part. It is recommended to change this value to -0.005 inch (-0.127 mm) to prevent the stabilizer wall from penetrating too deep into the part and causing leak points.
- The units of these values are the same as the units selected within Insight (inch or mm).

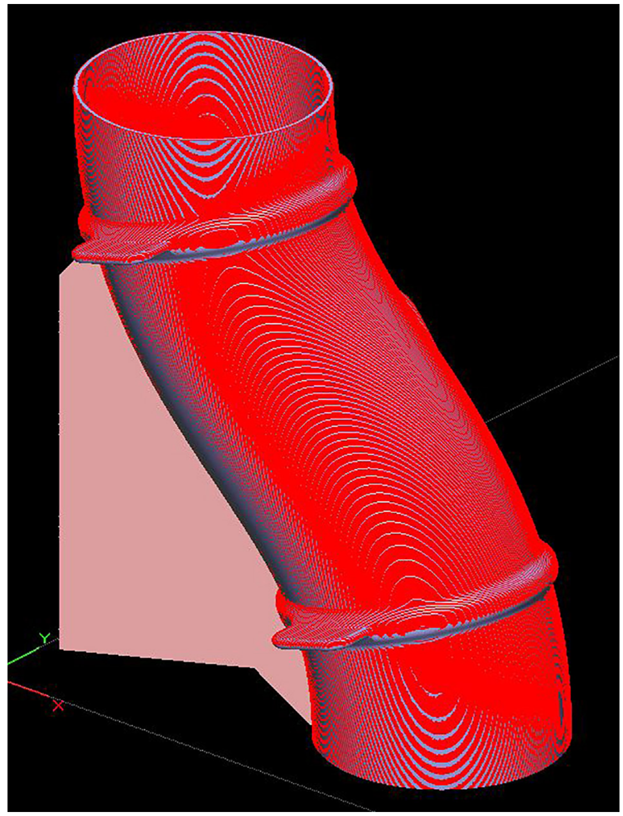


Figure 22: A stabilizer wall (salmon) provides additional support to tall ducts.

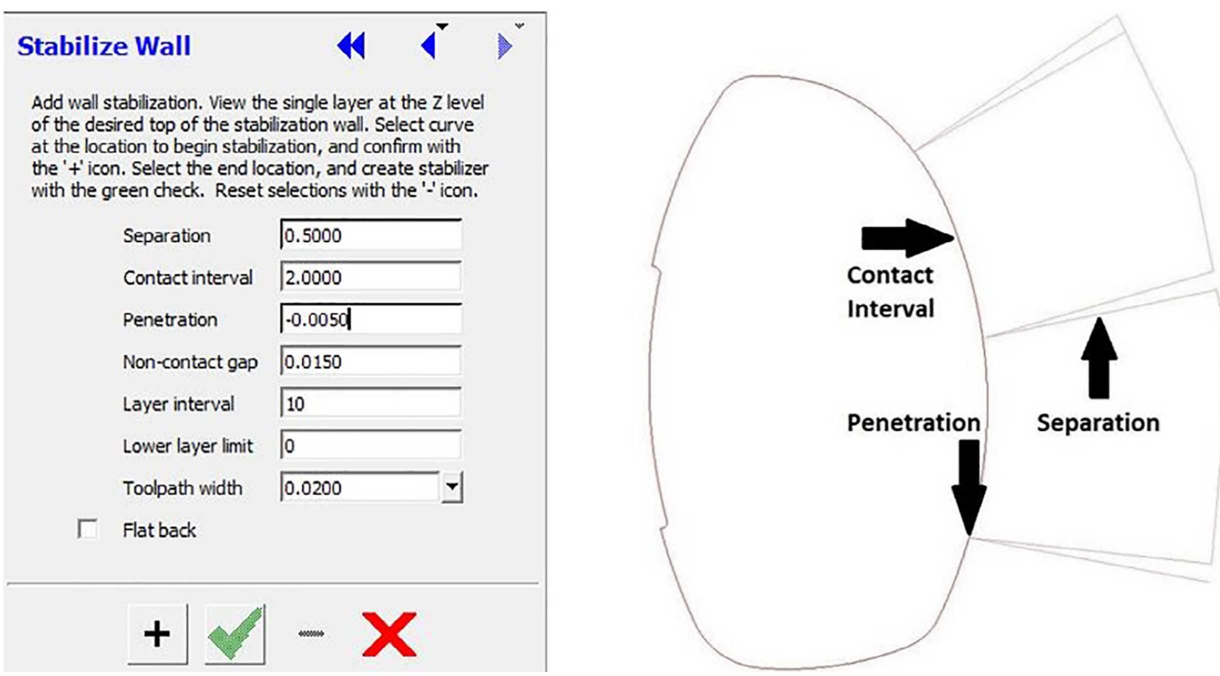


Figure 23: A stabilizer wall tailored to the specific part geometry.

6. Post-Process Sealing

Following the Insight best practices above reduces the leaking of an FDM duct, but typically does not completely seal the duct (Figure 24). If an airtight duct is required, especially for higher-pressure applications, post-process sealing of the duct must be performed. There are multiple methods for sealing FDM ducts, but most sealing methods detailed in this guide use an epoxy to seal the ducts, specifically BJB TC-1614, a low viscosity, high temperature epoxy formulated to penetrate into FDM parts for sealing. An epoxy coating is an effective way to seal porosity in a part and epoxy may be used with any of the other post-processing methods as a spot application to fill imperfections and holes. To maintain the FST rating of the duct for certain aircraft applications, it may be required to use an FST epoxy.

Figure 24: FDM parts exhibit a process-induced porosity that is undesirable in ECS ducting. If the pressure loss incurred from the presence of the porosity is not tolerable, use a secondary process to seal the parts.

6.1 Brushing

Brushing epoxy on the duct is often the quickest and easiest method of sealing for low volume applications. The epoxy can be brushed on, applied using a roller, or wiped on using a cloth.

6.2 Spraying

Low viscosity epoxies can also be applied through a spraying method using traditional paint gun equipment (Figure 25). Other sprayable sealers can be applied using this method as well.

Figure 25: Spraying epoxy reduces the manual labor for post-process sealing compared to brushing.

6.3 Vacuum Impregnation

Vacuum impregnation or vacuum infusion is a method that can be used with small vacuum pots (Figure 26) or existing, large impregnation centers offered by multiple sealing companies. Sealing using this method ensures that the sealer fills all voids within the part and is not a surface-only coating. This method is recommended for high-pressure applications (>15 psi [1.034 bar]).

6.4 Painting

Painting the part provides sufficient sealing for many low pressure (<10 psi [0.689 bar]) applications (Figure 27). Ducts should be lightly scuffed, cleaned and then painted in a similar manner as other plastic components, using similar paints.

Figure 26: Vacuum impregnation can be performed using small vacuum pots or large industrial impregnation centers.

Figure 27: Standard aerospace or automotive paints formulated for plastics can be used to seal FDM ducting for low-pressure applications.

7. Testing and Prospective Performance

Testing of multiple toolpath parameters and sealing methods was performed in order to determine the ideal Insight parameters for reducing leakage and proving multiple sealing methods, enabling easy adaptation of this application. Life cycle testing and crush testing proved the resilience of FDM ducting over pressure and temperature cycles and possible handling or kick loads that the ducts may experience during their lifetime. This section details the data that was highlighted in previous sections.

7.1 Leak Testing

7.1.1 Test Setup

A test setup was devised to measure the leak rate of a 2.5 inch (63.5 mm) diameter, 6 inch (152.4 mm) length of FDM ducting, shown in Figure 28. The test setup used a pressurized air inlet source, controlled by a valve, pressurizing the FDM duct to a specific pressure, holding the duct at that pressure, and then measuring the leak rate using a flow sensor. Ducts were tested every 2.5 psi (0.172 bar) up to 15 psi (1.034 bar). A steady-state pressure was achieved by adjusting the inlet valve to control the incoming air-flow rate until the duct was held at a steady-state pressure, measured by the pressure gauge. The in-line flow rate sensor was used to measure the set inlet air-flow rate required to keep the duct pressure constant, recorded as the leak rate of the duct.

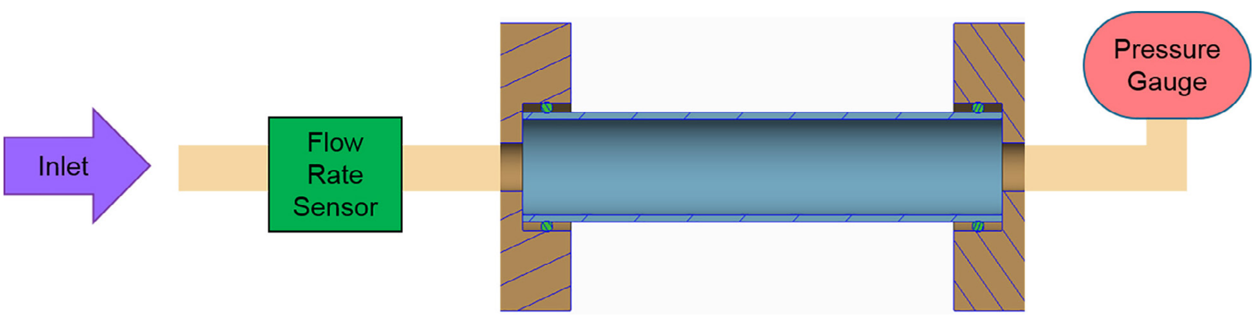


Figure 28: A leak-rate test fixture designed to test the leak rate of FDM ducting at various pressures.

Figure 29 displays a constructed test fixture. Aluminum end plates, machined with 2.5 inch (63.5 mm) diameter holes, received the FDM duct and are held together with threaded rods and wing nuts. The duct was sealed into the fixture with RTV (room temperature vulcanization) silicone preventing leaking at the connection points and was allowed 24 hours to cure before testing. The duct was pressurized to ~5 psi (0.345 bar) and soapy water was applied to the connection points sealed with RTV to ensure that no air was leaking from the seal (the soapy water would produce visible bubbles if leaking was present). Inlet airflow was provided through a valve from standard compressed shop air and an inline-flow rate sensor, incorporated to measure the inlet flow rate. Duct pressure gauge measurements were integrated into the opposite end of the test fixture.

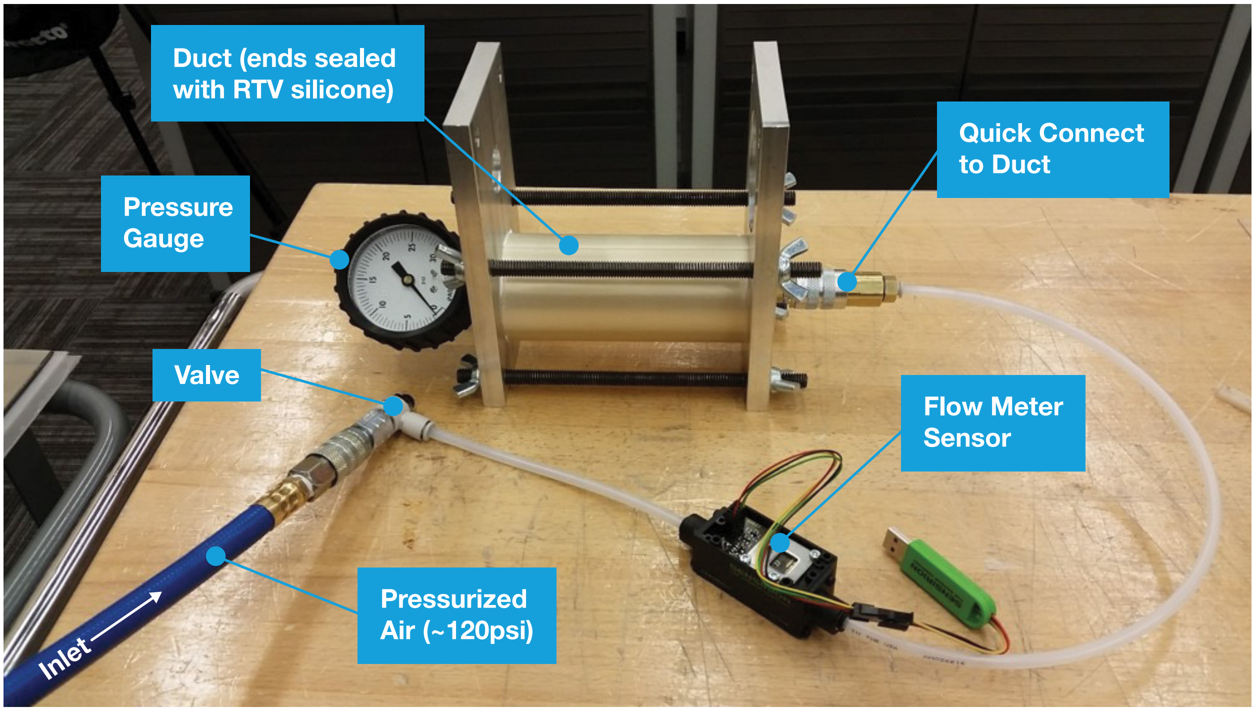


Figure 29: A basic test fixture was constructed to measure the leak rate of the ducts.

7.1.2 Seam Conditions

Initial testing of FDM ducting determined that the majority of leakage was coming from the seam of the duct. A combination of seam conditions controlled by Insight were tested to determine the best seam type to minimize leakage. Two seam parameters were varied in testing, seam alignment and linking contours, as well as the angle of the duct while building (Table 1).

Seam Test Matrix

0.040 inch (1.016 mm) thick, 2-contour only straight ducts

Test	Seam	Contour	Orientation
1	Aligned	Linked	Vertical
2	Aligned	Linked	45° Angle
3	Aligned	Unlinked	Vertical
4	Aligned	Unlinked	45° Angle
5	Random	Linked	Vertical
6	Random	Linked	45° Angle
7	Random	Unlinked	Vertical
8	Random	Unlinked	45° Angle

Table 1: A test matrix created to test varying seam conditions.

The duct that was tested, using various seam conditions, was a straight duct of 2.5 inch (63.5 mm) diameter, 6 inch (152.4 mm) length, and 0.040 inch (1.016 mm) thick (Figure 30).

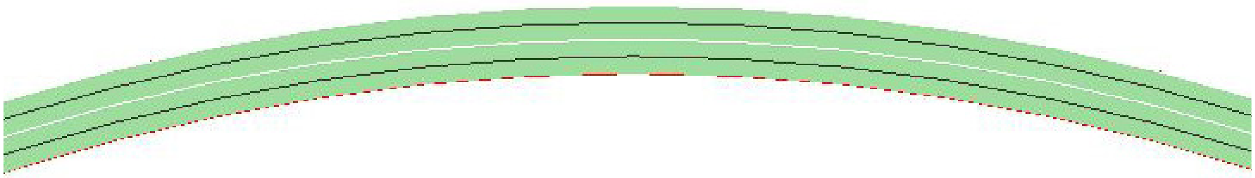


Figure 30: Seam conditions tested using a straight duct, 0.040 inch (1.016 mm) thick that consisted of two contours, each 0.020 inch (0.508 mm) thick.

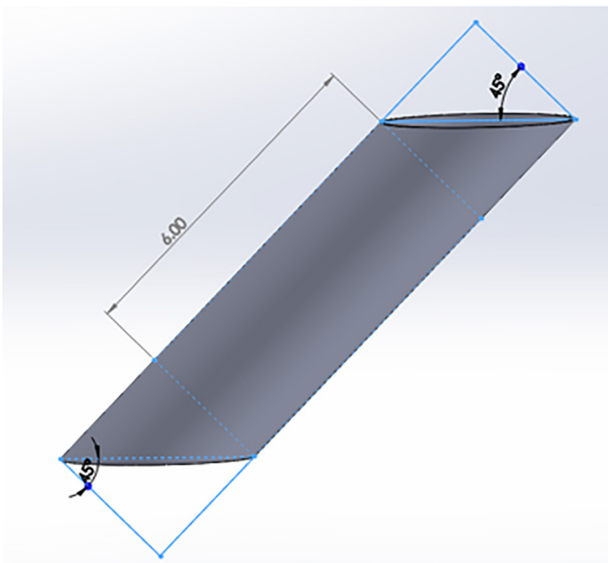


Figure 31: The 45-degree ducts, overbuilt by design, later cut to size.

The test duct was built vertically in the machine's build chamber at a 45-degree angle to determine what effect the steepest angle recommended for FDM ducting would have on leak rate. The 45-degree ducts were designed as shown in Figure 31 in order to have a flat surface to build on the platen rather than a knife edge.

The 45-degree ducts were then cut (Figure 32) to six inches in length with flat, perpendicular faces so that they would fit in the test fixture.

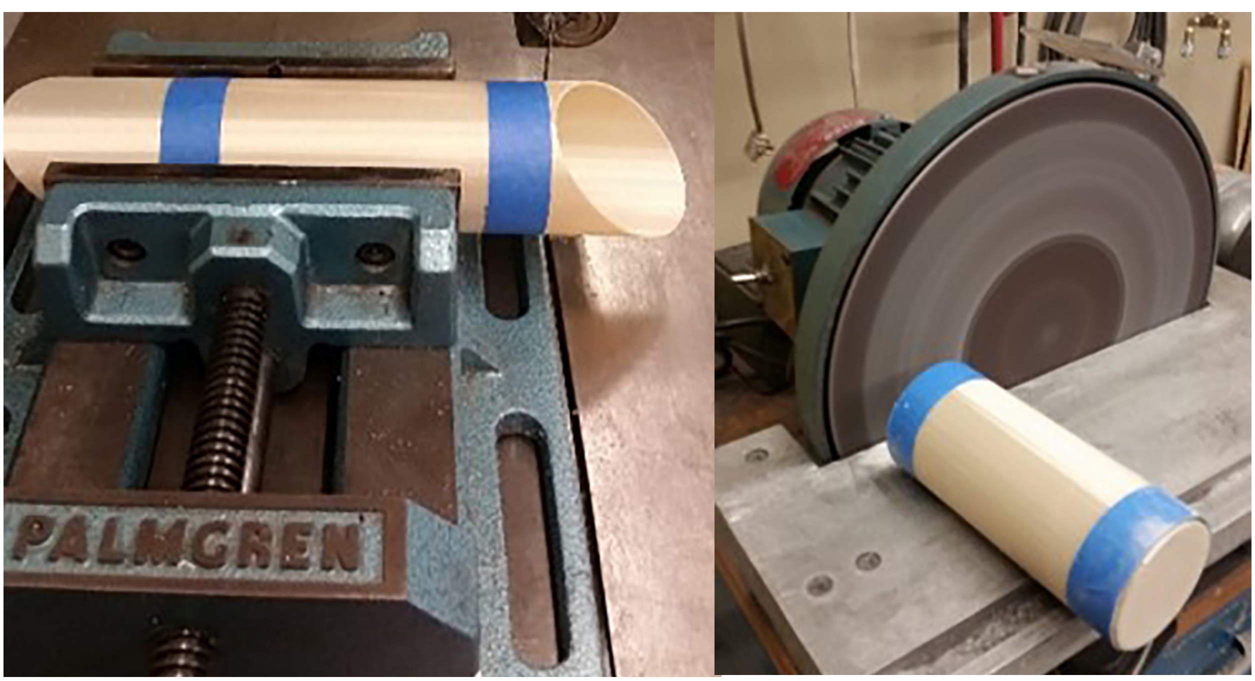
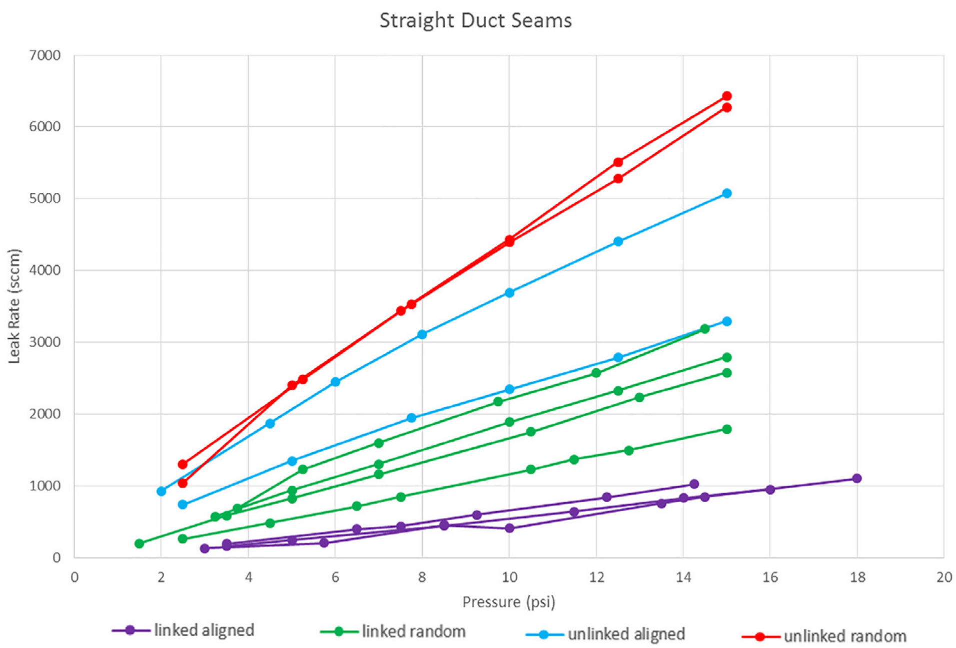


Figure 32: A band saw was used to trim the excess material off of the 45-degree ducts and the ends were sanded smooth.

The leak rate of each seam combination was recorded and is shown in Figure 33 for ducts that were built vertically (straight) in the build chamber and for ducts that were built at 45 degrees. The duct pressure is shown on the horizontal axis in pounds per square inch (psi) and the flow rate is listed on the vertical axis in standard cubic centimeters per minute (sccm), where 1,000 sccm is equal to one liter per minute (lpm). The data indicates that linked aligned seams performed best, followed by linked random, unlinked aligned, and unlinked random respectively for the straight ducts.

Unlinked random performed better than unlinked aligned for 45-degree ducts. Linking seams has the greatest effect on leak rate by building the two contours in a single, connected toolpath rather than having multiple starts/stops, with the potential of introducing air passages throughout the duct.



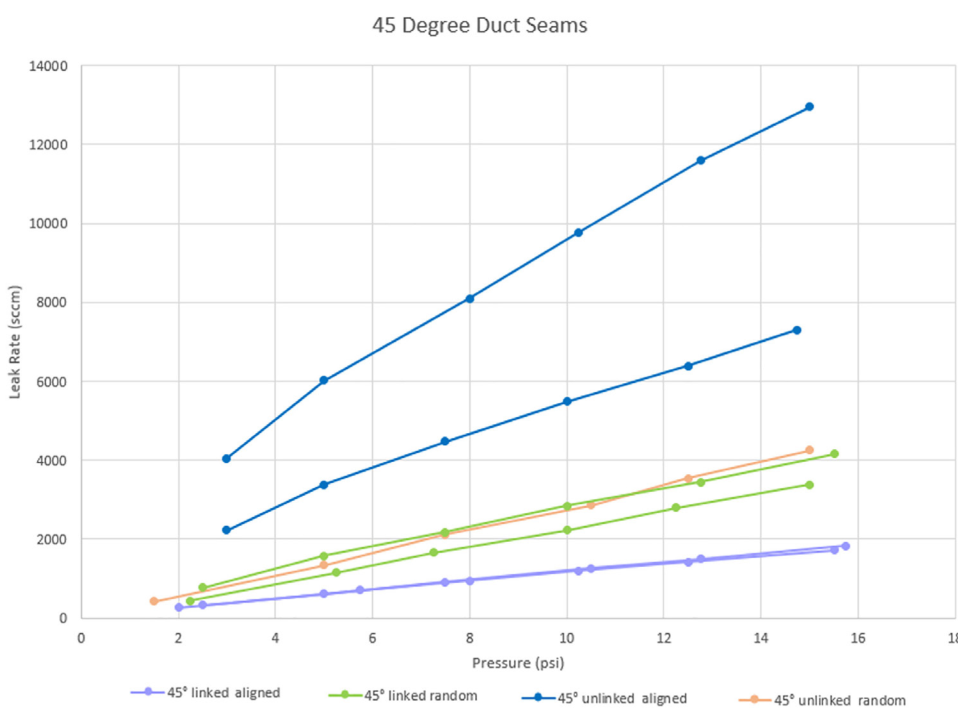


Figure 33: Leak rate data for the four seam combinations on vertically built ducts and ducts built at 45 degrees.

A comparison of the two lowest leak-rate seam conditions for straight ducts and 45-degree ducts are shown in Figure 34. The data indicates that the 45-degree ducts did not perform as well as the straight ducts. The drop in performance is likely due to the reduced bonding area between layers that occurs when building at a 45-degree angle compared to vertical, allowing air to pass more easily through the duct wall.

7.1.3 Fill Patterns

It was desired to determine the effect of rasters on sealing. This was tested by thickening the duct to 0.080 inch (2.032 mm) such that rasters could fit into the duct. Figure 35 shows the two fill patterns compared, testing on straight ducts and 45-degree ducts.

Figure 34: Leak rate comparison between straight and 45-degree ducts.

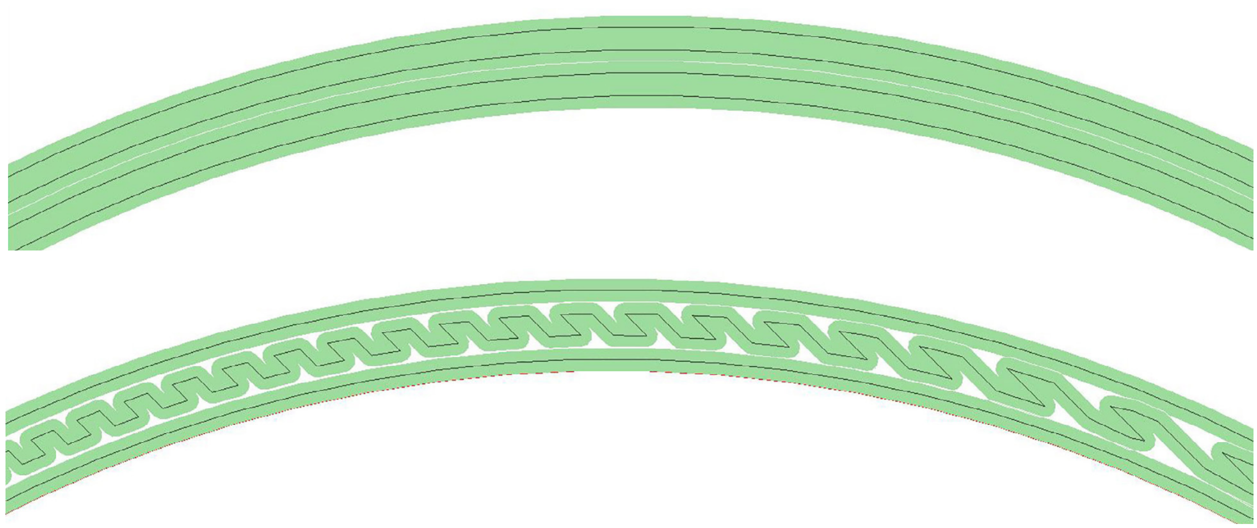


Figure 35: A duct consisting of four contours compared to a duct of two contours with a raster fill in between.

Figure 36 shows the leak testing results for this geometry. The increased porosity of the fill generated an expected, increased leak rate. The effect of the 45-degree angle on the performance of the duct was non-existent, since there was adequate surface area to seal similar straight ducts, due to the increased duct thickness.

Producing a duct entirely of contours is the ideal case, confirmed by the data above. In bifurcation or mounting feature areas, where the duct thickens, rasters are often necessary. These features need special attention when sealing using a manual method, such as brushing or spraying.

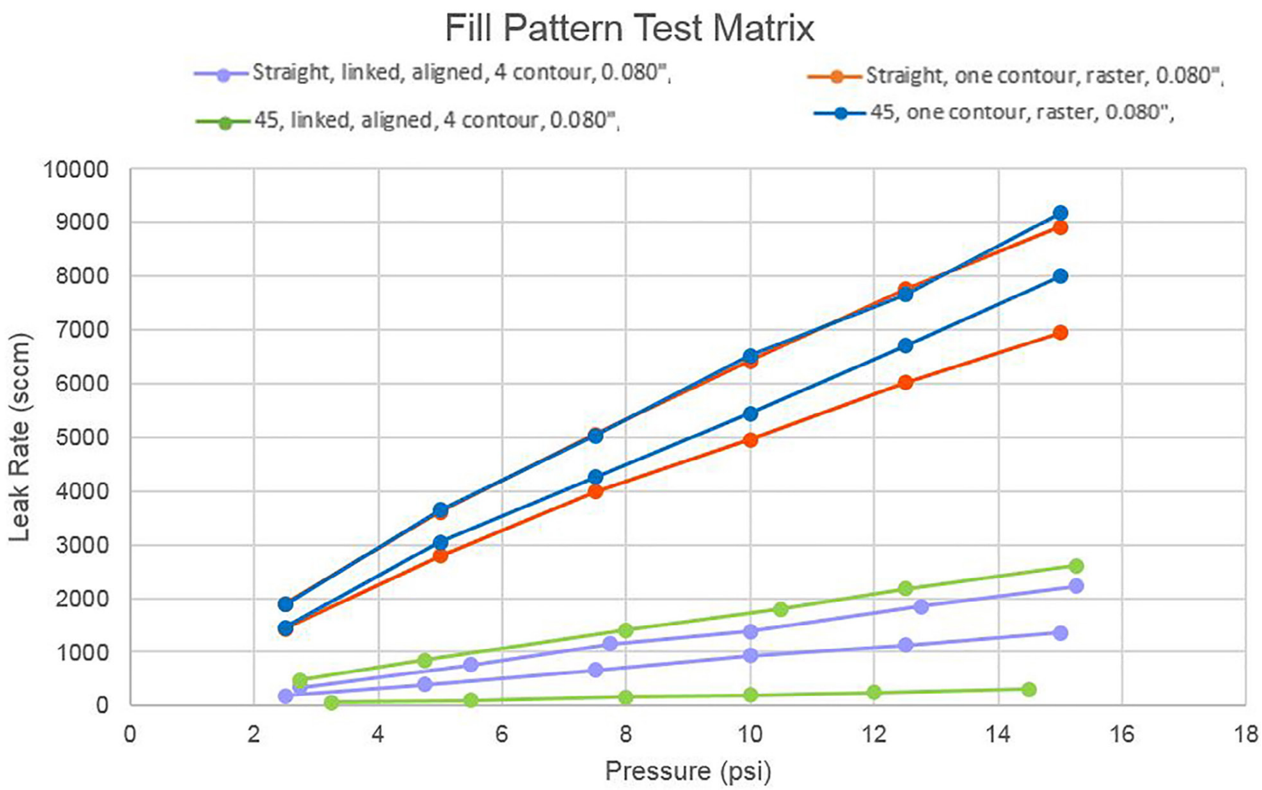


Figure 36: Rasters allow for increased porosity in ducts, in some cases, unavoidable with certain duct geometries.

7.1.4 Remnant Fill

A different duct geometry tested remnant fill (Figure 37). This duct had voiding that would be typical of an S-shaped duct, which would benefit from remnant fill. This fill better represents the geometry of ECS ducting, compared to that of a straight tube used in previous testing, limiting the number of variables.

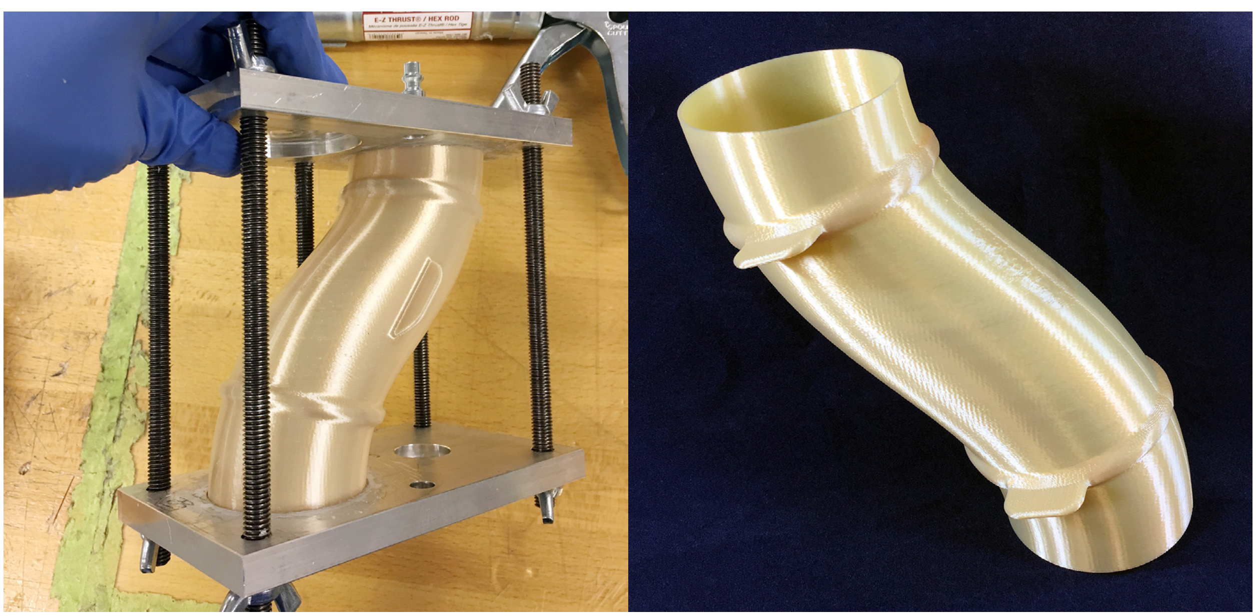


Figure 37: An S-shaped duct with reinforcement areas and integrated brackets used for remnant fill testing due to multiple voids when processed using standard algorithms.

Filling these voids with remnant fill (Figure 38) significantly reduces the leak rate of the ducts (Figure 39). Seams are the same for both remnant fill and standard fill and removed as a variable during this testing. A narrow strip of epoxy, carefully applied to the aligned seams, seals them so leaking only occurred in raster or voided areas of the duct. Sealing the seams provided a more accurate comparison of the remnant fill effect to the standard fill.

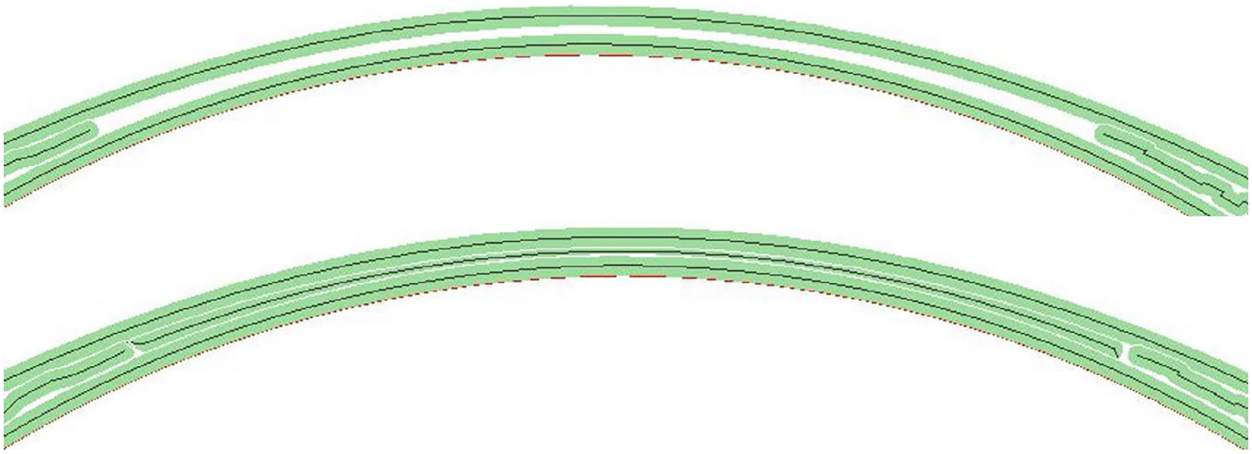


Figure 38: Filling voids not only increases the structural integrity of thin-walled parts, but also promotes sealing.

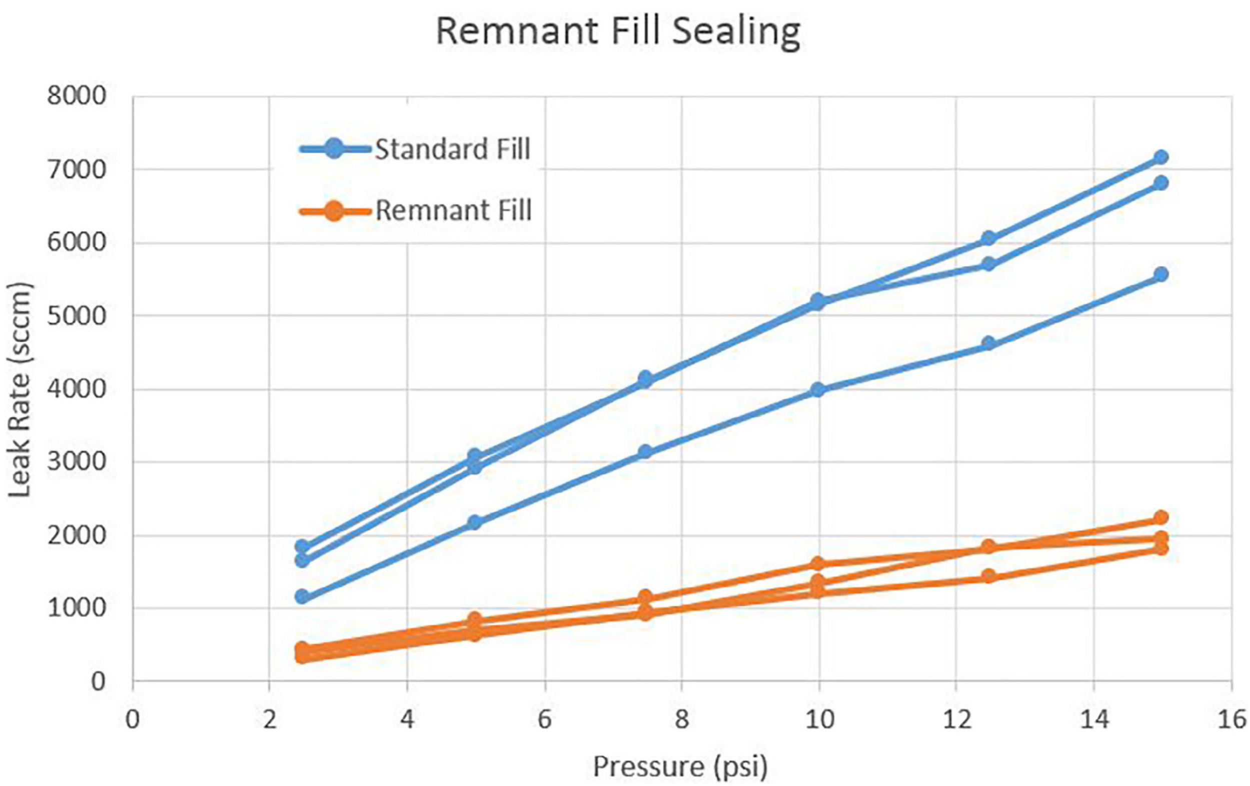


Figure 39: The effect of remnant fill on sealing is distinctly apparent when seams have been sealed.

7.2 Sealing

The various post-process sealing methods mentioned in Section 6 were performed and tested up to 15 psi (1.034 bar) on straight ducts consisting of two contours with linked aligned seams. Table 2 shows the results of these sealing methods. The epoxy used in all of the sealing methods was BJB TC-1614. A higher viscosity FST epoxy (Huntsman Epibond 8000 FR) was also used to seal only the seam of a duct to prove equivalency for higher viscosity epoxies as well as FST-compatible epoxies. This epoxy also sealed the duct up to 15 psi (1.034 bar).

The painted ducts were sprayed with an aerospace primer, one with a heavy coat and one with a light coat, shown in Figure 40. As Table 2 shows, the heavy paint coat sealed much better than the light coat. For other ducts that did not seal, see Figure 41.

Duct Type	Sealed?	Leak Rate (sccm) at 15 psi (1.034 bar)
Baseline	No	1000
Epoxy Brush Entire Duct	Yes	0
Epoxy Brush Seam Only	Yes	0
Epoxy Vacuum Infuse	Yes	0
Epoxy Spray	Yes	0
Heavy Paint	No	20
Light Paint	No	555

Table 2: Multiple sealing methods are compatible with FDM ducting

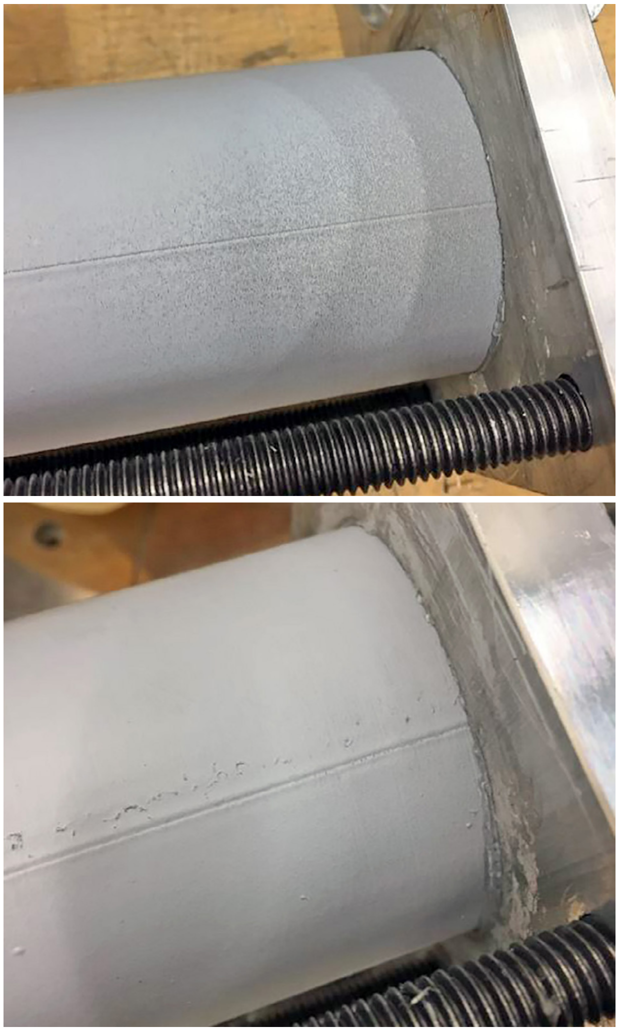


Figure 40: A light (top) and heavy (bottom) coat of paint was applied to ducts to determine the leak rate of different coating thicknesses.

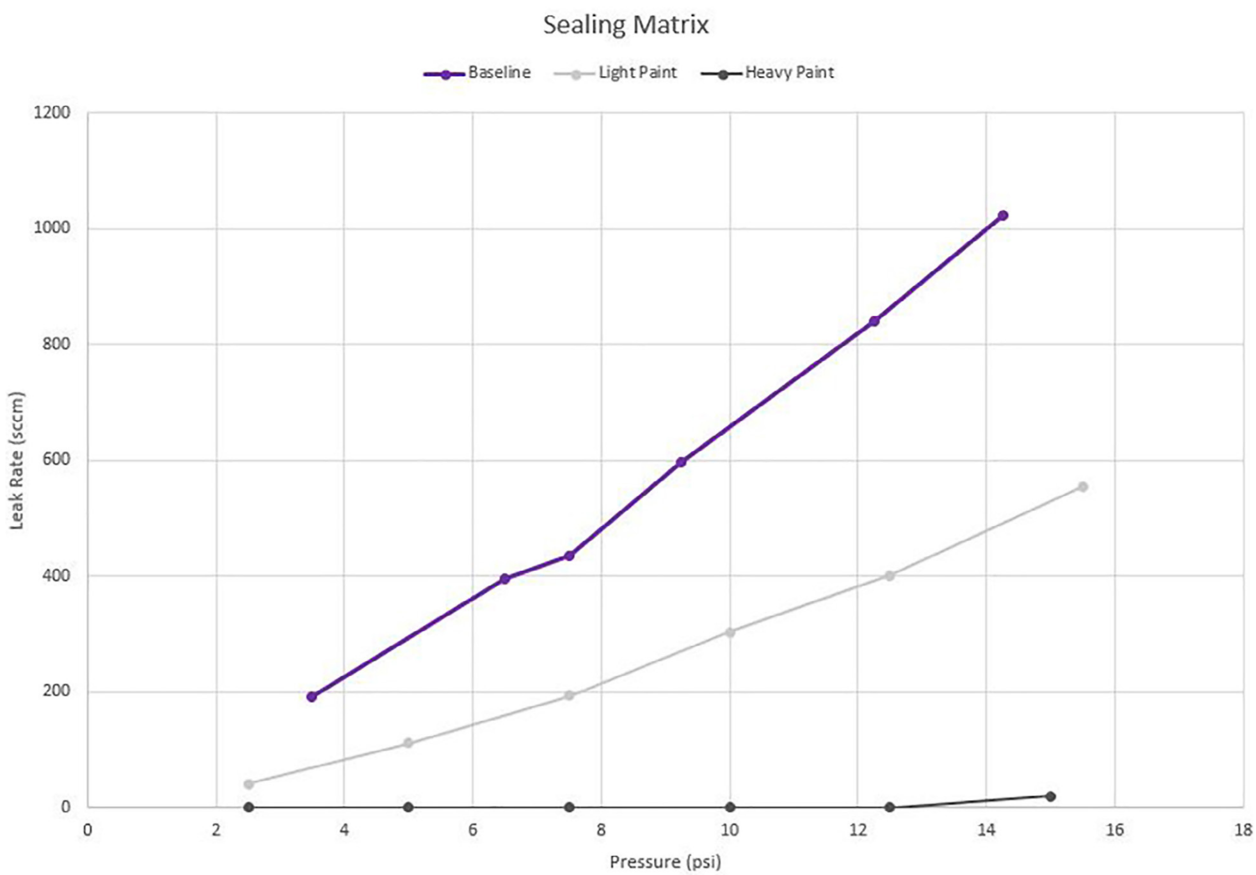


Figure 41: A light coat of paint is enough to cut the leak rate roughly in half.

7.3 Burst Proof Testing

Burst proof testing determined the limitations of the printed ducts. ASTM D1599 was used as a guide and the ducts were subject to slow pressurization. Two-contour ULTEM 9085 ducts were exhaustively tested at or above 50 psi (3.45 bar) and did not fail. Low-pressure ducting rarely exceeds 50 psi (3.45 bar); this is therefore a valuable finding. Full burst testing was abandoned because above about 75 psi (5.17 bar), the test fixture started leaking such that the slow pressurization could not be maintained. The ducts were, however, subject to rapid pressurization over a few seconds to 125 psi (8.62 bar) and they also did not fail. Therefore, the pressure capability with respect to burst is likely much higher than 50 psi (3.45 bar) for two-contour ULTEM 9085 ducts. More exhaustive testing with this specific configuration is necessary if pressures higher than 50 psi (3.45 bar) are required.

7.4 Mechanical Testing

7.4.1 Cross-diameter deflection

Straight tubes of ULTEM 9085, tested in a compression-oriented load frame, did not fail and showed little short-term hysteresis or permanent set. The samples were then loaded until failure. Load vs. deflection was measured and samples were cycled with deflection control increasing the deflection by 0.100 inch (2.54 mm) each cycle until the 2.5 inch (63.5 mm) diameter tubes were compressed by 1 inch (25.4 mm). The two- and three-contour samples were crushed flat with 1000 lbs (4448 N) of pressure. With the load removed, the samples were almond shaped with permanent deformation. The four-contour samples failed at the seam after around 0.8 inch (20.32 mm) of deflection (Figure 42) at the seam which was located on the bottom platen of the load frame in an attempt to minimize the effect that seam might have.

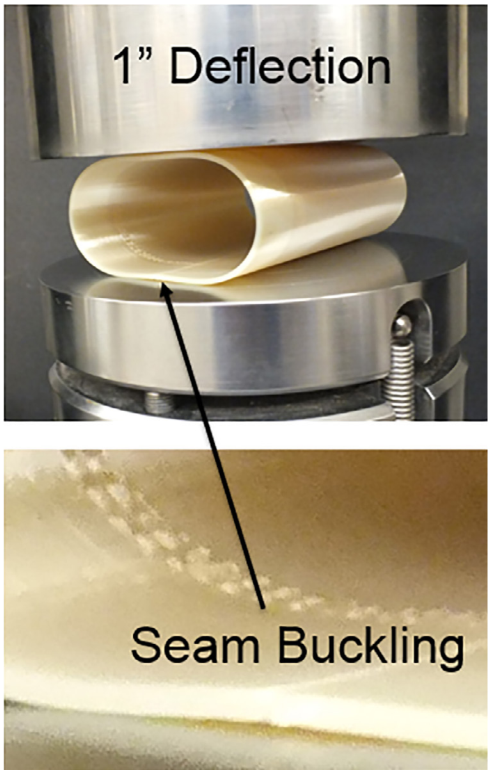


Figure 42: Deflection testing of four-contour ULTEM 9085 duct.

As expected, the cross-diameter deflection testing showed a significant resilience with the ULTEM 9085 tubes. The two- and three-contour-wall thickness samples rebounded from 1 inch (25.4 mm) of deflection, nearly immediately and completely, after removing the load. They showed very little permanent deformation; on the order of 0.020 inch (0.508 mm) across 2.5 inch (63.5 mm). The four-contour sample split at the vertical seam when deflected around 0.8 inch (20.32 mm).

When loaded to 1000 lbs. (4448 N), the two- and three-contour samples did fail and were permanently and significantly deformed. Figure 43 shows post-test sample pictures.

Figure 43: Post-test results when loaded to 1000 lbs (4448 N).

Stratasys Headquarters

7665 Commerce Way,
Eden Prairie, MN 55344
+1 800 801 6491 (US Toll Free)
+1 952 937-3000 (Intl)
+1 952 937-0070 (Fax)

1 Holtzman St., Science Park,
PO Box 2496
Rehovot 76124, Israel
+972 74 745 4000
+972 74 745 5000 (Fax)

stratasys.com
ISO 9001:2008 Certified