



FDM Lightweight Structures

DESIGN GUIDE

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Many aerospace and automotive applications require parts with a very high stiffness-to-weight ratio. Because of the high level of design freedom available when designing parts to be built with FDM Technology™, special structures can be created to optimize material use and maximize part stiffness. These structures can be created with the automated fill pattern capabilities of Insight™ software. In cases that require high structural customization or a higher strength-to-weight value than automated fill patterns can deliver, use the “single bead” design methods detailed in this document.

1. Materials

The FDM process offers several material options, each with attributes that make it suitable for a variety of lightweight structural applications. For help in selecting the appropriate material for a given application, consult Table 1 and Figure 1.

2. Low Density, Sparse Fill and Shell Parts

Sparse fill and shell parts have a high polar moment of inertia and consequently provide a high stiffness-to-weight ratio. In both cases, the geometry is brought into Insight software as a solid body representing the outer mold line (OML) of the part. The internal sparse fill or hollow areas are generated within Insight.

Table 1: Material Characteristics Relevant to Single-Bead Design

MATERIALS	YOUNG'S MODULUS (MPa)	TENSILE STRENGTH (MPa)	DENSITY (kg/m ³)	TENSILE SPECIFIC STIFFNESS (kg/m ³)	TENSILE SPECIFIC STRENGTH (Nm/kg)	OTHER ATTRIBUTES
ASA	2010	33	1050	1.91	0.031	High stiffness-to-weight ratio. Best bridging capabilities for making lightweight, hollow structures. Very isotropic material properties.
PC	1944	57	1200	1.62	0.048	Good combination of strength and stiffness.
ULTEM™ 9085 resin	2150	69	1340	1.60	0.051	Best material for durability and strength or for temperature resistance. Limited chemical resistance.
PC-ABS	1810	34	1100	1.65	0.031	Highest impact resistance. Use for components subject to impact or high cyclic loading.
ULTEM™ 1010 resin	2770	81	1270	2.18	0.064	Highest stiffness, highest temperature resistance. Best chemical resistance. Lower ductility.
FDM Nylon 12	1282	46	1000	1.28	0.046	Use where extreme impact resistance or fatigue resistance is needed. Lowest specific stiffness. Very isotropic material properties. High chemical resistance.

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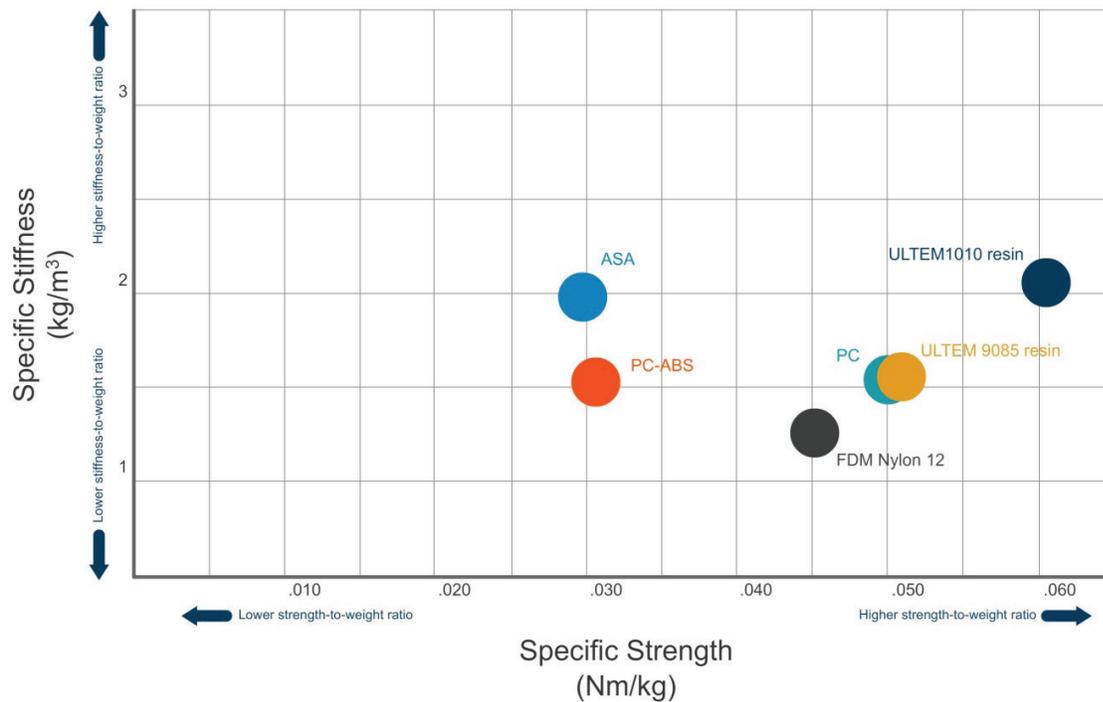


Figure 1: Overview of FDM materials comparing specific stiffness to specific strength.

2.1. Sparse Fill

Sparse fill was originally created to reduce material use for prototype parts that were structurally unstressed and occupied a larger volume than necessary. As FDM proves useful in more manufacturing applications, it is increasingly common for structural parts to be designed with sparse fill to increase the stiffness-to-weight ratio.

Sparse fill can be used much like a core material in a composite sandwich structure. A part can be designed so that the skin or shell is constrained and supported by sparse fill. This allows the part's area moment of inertia to be high, providing an ideal distribution of mass that is conducive to part stiffness and bending strength, like an I-beam, but in three dimensions. Sparse gaps can be used with any number of contours. Suitable sparse gaps depend on the loading vs. weight requirements.

Depending on the required surface finish of the cap layers or the number of cap layers, a sparse gap as large as 0.5 inch may be used. Larger sparse gaps create a waffling effect in the cap layers that takes multiple layers to overcome.

2.2. Shell Parts and Tubular Structures

Alternatively, by making use of self-supporting angles and the ability of the FDM process to bridge gaps, solid volumes can be created as shells with hollow interiors. This idea also applies to creating hollow tubular structures. A shell can be created from a solid body by using a custom group and unchecking the rasters box in the toolpath settings. Shell parts can be created with any size or number of rasters, provided the angle of the wall does not cause a gap between the rasters from layer to layer. "Bulkheads" and caps can be created along the Z direction of a shell by employing a custom group for a number of layers. The custom groups may contain either sparse fill or solid toolpaths.

The first few layers of the bulkhead will attempt to bridge the gap between the shell walls. Consequently, they will droop until a solid foundation is created. This is much like the waffling effect of sparse fill but on a larger scale. The larger the gap, the farther the initial layers will droop and the more layers it will take to recover to a state of normal deposition. Internal bulkheads are capable of bridging gaps up to about two to three inches. For a larger gap, it may take up to 10 layers to bridge and create a stable bulkhead.

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3. Single Bead

Certain applications that require thin-walled geometry are not ideally suited for the standard toolpath generation process within Insight. The single-bead process allows structures to be built by defining toolpaths directly in the CAD file. This design method achieves wall dimensions as thin as a single toolpath, as illustrated in Figure 2.

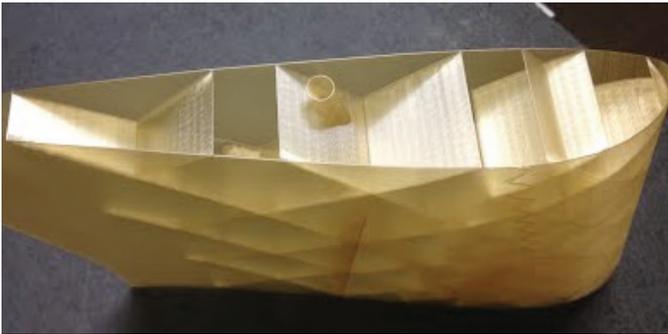


Figure 2: Example of a single bead structure.

3.1. CAD Generation and Insight Processing

When creating CAD geometry for single-bead parts, the orientation of the part must be selected before the model is created. Every measurement pertaining to build tolerances, clearances and interference must be relative to the X-Y plane of the build. In the single-bead design processes, the CAD model consists of surfaces that when sliced, provide a centerline for the creation of toolpaths as shown in Figure 3.

A single toolpath centerline results in a wall thickness equal to one toolpath width. Multiple toolpath widths can be “stacked” in the X-Y build plane to create walls with thicknesses that are a multiple of the toolpath width. Because the toolpath is generated using the surface as a centerline, the resulting printed toolpath will extend out from the centerline by one-half the toolpath width on either side. Because of this, the CAD model will need to be offset by one-half the toolpath width with respect to the OML geometry or connections between adjoining toolpaths.

Imported surfaces can be open or closed shapes with respect to the X-Y build plane. During toolpath generation however, the geometry must be open to be recognized as a single-bead centerline. If the slice of the shape results in a closed curve, the slice must be split in Insight, using the *Split curve* tool. It is

sometimes convenient to split multiple curves at once by selecting all closed curves within the model using the *Select closed curve* filter. Once imported and sliced, an open curve can be assigned as a single-bead toolpath by inserting the curve into a custom group. The *Open curve* width parameter in the group's toolpath settings dictates the width of the bead.

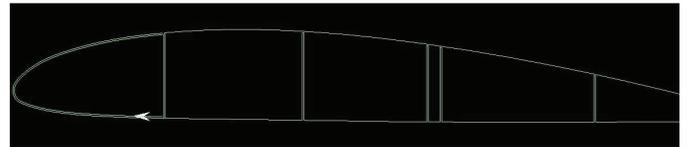


Figure 3: Resulting centerline of a toolpath generated by slicing a surface. The outer surface of the shape will lie one-half the toolpath width beyond the external surface. Gaps between adjacent toolpaths prevent excessive interference or two toolpaths from occupying the same space.

3.2. Self-Supporting Angles

Similar to solid-body parts, single-bead structures require support material for angles of 45 degrees or less from horizontal. Because standard support generation is not easily employed with single-bead structures, it is recommended that the majority of features conform to the self-supporting angle, especially internal features and core structures.

Additionally, because single-bead structures are very thin, large angles can cause the toolpath in a subsequent layer to have a large enough shift in the X-Y direction that there is little bonding area between layers (see Figure 4). If the angle is severe enough, there will be a gap between layers. Areas that don't conform to self-supporting angles should be isolated and built as solid bodies embedded within the single-bead body (see Section 5 – Hybrid Parts).

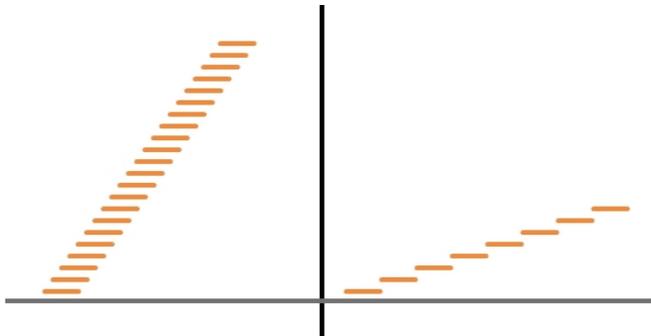


Figure 4: Left: self-supported single-bead wall; right: an extreme-angle single-bead wall causing poor bonding area between layers.

3.3. Clearance and Interference Between Toolpaths

The optimal overlap between toolpaths depends on factors such as geometry, material, and tip life. The greater the interference, the stronger the bond, at the expense of increased perturbation of a toolpath by the deposition of the subsequent toolpath.

Perturbations in the toolpath are created from physical obstructions in the toolpath or from small-radius corners. The perturbations ring throughout the drive system of the head gantry and show up as a damped sine wave in the deposition across some distance proportional to the severity of the perturbation (see Figure 5).

As a starting point, it is recommended that the interference between adjacent contours start at 10%-15% of the contour width. If problems arise due to the initial interference value, it may be adjusted accordingly.

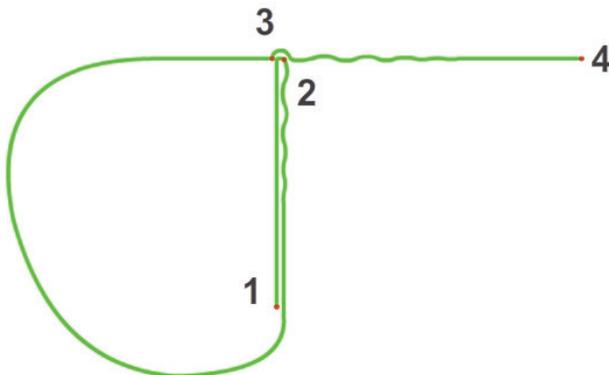


Figure 5: A toolpath starting at point 1 and ending at point 4 will be perturbed when transitioning through a sharp radius corner at point 2 or when encountering a physical interaction with a previous deposition at point 3.

Because we are designating toolpath centerlines, the clearance between adjacent surfaces in the CAD file must account for the toolpath width. As a result, the clearance between surfaces in CAD will not be equivalent to the resulting clearances of a toolpath. Notionally adding in the thickness of half the toolpath width to either side of the surface will represent the boundary of the physical toolpath. If an interference in physical toolpaths is desired, the spacing of the surfaces in CAD can be calculated as the toolpath width minus the desired interference (see Figure 6).

Because the end of a bead deposition extends beyond the end of the toolpath as a semi-circle having a radius of half the toolpath width, the necessary gap required to achieve a given interference does not change regardless of the intersection angle between toolpaths.

In general, parallel toolpaths require less interference because of the head's direction of motion, while toolpaths meeting at a 45 degree angle require the most interference to create a solid structural bond. Perpendicular toolpaths have an optimal interference somewhere between the parallel and 45 degree cases.

It is usually sufficient for all interference angles to be consistent within a geometry, regardless of intersection angle, to simplify CAD construction.

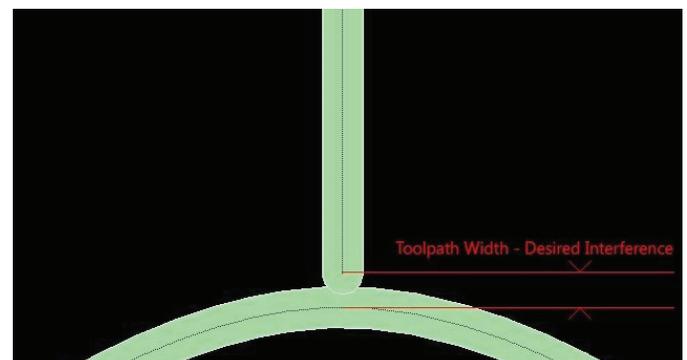


Figure 6: Clearance for adjacent open-curve toolpaths in a single-bead structure. CAD-defined clearance is given by the toolpath width minus the desired interference.

4. Support Considerations

Special considerations exist for parts created using the single-bead method, as well as for parts that have a high aspect ratio. Basic methods for support generation and part stabilization are automated within Insight. Advanced methods give higher levels of flexibility and involve the creation of supports within CAD similar to the single-bead design method.

4.1 Support Structures for Non-Self-Supporting Thin-Wall Geometries

It is not always possible to create a geometry completely free from self-supporting angles. Support material must be generated in a roundabout way for open curves. Insight does not consider open curves for support generation. If support material is needed for a single-bead part, a solid body representing the final dimensions of the part must be created, sliced, and imported into a custom group using the *Combine slice curve* files command. Insight can generate support for the solid body. Once support is generated for the solid body, solid curves can be selected with a color filter applied to the custom group designating the temporary geometry to be deleted.

4.2 Stabilizing Tall Parts Within Insight

For tall and thin parts, the wall stabilizer feature in Insight should be used to prevent part flutter near the top of the build. Wall stabilizers can be generated for both closed-boundary and open curves. An open curve will be recognized by the wall stabilizer generation algorithm and its values will be automatically adjusted to account for the toolpath width designated in the custom group.

4.3 Stabilizing Tall Parts Within CAD

Creating stabilizers directly in CAD rather than generating the curves in Insight allows for greater flexibility in the stabilizer's shape and complexity. CAD stabilizers may also be used to connect multiple parts together, increasing the effective footprint and stability of the parts.

In the same method as single bead, CAD-generated wall stabilizers should have a CAD-defined spacing of the toolpath thickness minus the desired interference, relative to the X-Y build plane. Unlike structural components, the wall stabilizer should have a minimal amount of penetration into the part to facilitate

removal. A suggested starting point is 0.001 inch of interference. Interference should be increased for additional stability or decreased for ease of removal based on the results of the first build.

It is good practice to alternate the toolpath direction of the wall stabilizer every so often so that if a layer fails and the stabilizer begins to droop on one side, the next layer will resolve the problem. It is also good practice to end the stabilizer toolpath so that it is pointing away from the part as shown by the blue lines that trail off from the vertical blue lines in Figure 7. This will prevent a trail of material leaving the wall stabilizer from getting redistributed into the part. This can be accomplished by changing the direction of the stabilizer where it contacts the part by an angle of approximately 45 degrees.



Figure 7: CAD-generated wall stabilizer in blue showing a 30 degree angle directional change to end away from the part.

4.4 Manual Support Generation

In certain instances, it is desirable to generate support material features directly in CAD. Manual support features can be imported as a separate CAD file using the *Combine slice curves* feature.

Instead, manual support features can be embedded within the working file provided that there is clearance maintained between the support body and the model body at all times in the X-Y plane. With either import method, the support boundary curves must be inserted into a custom group. The custom group will use settings preset for the chosen type of support material.

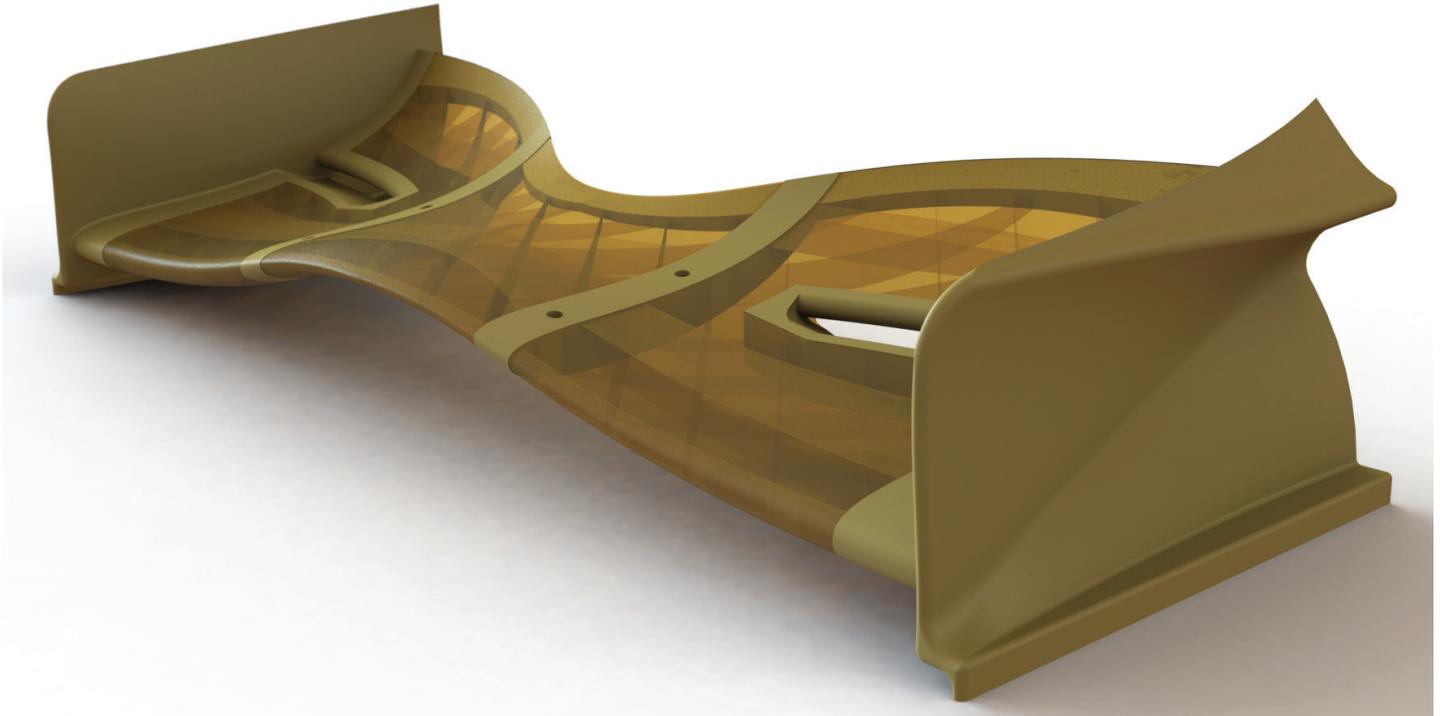


Figure 8: This image shows a hybrid part. The end caps and mounting sections in the middle are solid-body geometries. The wing surfaces are single-bead construction.

5. Hybrid Thin Wall and Solid Parts

When making a single-bead structure, it is often necessary to embed areas of solid-body geometry to facilitate complex shapes, non-self-supporting areas, or mounting points and brackets. The race car wing in Figure 8 demonstrates the need for a lightweight single bead structure with embedded solid body techniques used for reinforcing the mounting points. When embedding solid-body geometry, the offset of the toolpath width must be accounted for in the X-Y build plane only. The boundary between a solid body and a single-bead area requires a different formula for designating interference. Material will lie within the boundary of the solid body representation as opposed to around the single-bead centerline representation. Single-bead toolpaths adjacent to solid bodies in the X-Y plane should be offset by half the toolpath width minus the desired interference.



E info@stratasys.com / STRATASYS.COM

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)

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

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