Design Guide for 3D Printing with Composites
At several points in this guide we discuss different loading conditions with respect to print orientation. Due to the anisotropic nature of 3D printed parts, properties about or along the Z axis of printing — normal to the print bed — are different than those of the X and Y axes — parallel to the print bed. Properties and behaviors in this guide are framed in the context of the Z axis or the XY plane.

Important terms from Eiger, the Markforged 3D printing software, will be highlighted in BOLD CAPITAL LETTERS.
**Maximum part size**

**Desktop Series**
- X: 320 mm (12.60")
- Y: 132 mm (5.20")
- Z: 154 mm (6.06")

**Industrial Series**
- X: 330 mm (13.00")
- Y₁: 270 mm (10.63")
- Y₂: 250 mm (9.84") with fiber
- Z: 200 mm (7.87")

These build volumes reference the maximum bounding box your part must fit in to print on either a Desktop or Industrial Series Markforged composite printer. Industrial Series printers have a deeper print area when printing with only plastic. These guides serve as recommendations and may not reflect all implementations, as 3D printing is a geometry-dependent process. Unless otherwise specified, data is based on parts printed on Markforged composite printers at 100 micron layer height in Onyx with default print settings.

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**Plastic**

**Minimum part dimensions**

- X: 1.6 mm (0.063")
- Y: 1.6 mm (0.063")
- Z: 0.8 mm (0.031")

Minimum part size is limited to the extrusion width and height of each bead. The minimum number of roof layers, floor layers, and shells needed to print a part successfully.

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**Minimum unsupported overhang angle**

θ: 40°

This is the minimum angle to the horizontal at which a feature of a part can print without needing supports to hold it up. Eiger will generate supports for angles below 45°, but may not be needed in all cases.

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**Minimum hole diameter**

- XY: 1.5 mm (0.059")
- Z: 1.0 mm (0.039")

Holes with too small a diameter may close off during printing or print inaccurately. Horizontal surface holes (Z) print more precisely than vertical surface holes (XY).
Quick Reference Sheet

Minimum post diameter

**Z Layer features**
- **H:** 0.10 mm (0.004")
- **W:** 2.0 mm (0.079")

**Horizontal XY features**
- **D:** 0.20 mm (0.008")
- **H:** 0.80 mm (0.031")

**Vertical XY features**
- **D:** 0.20 mm (0.008")
- **W:** 0.50 mm (0.020")

An engraved feature is one that is recessed below the surface of the model. Common examples include lettering and texture. Engraved features may blend into the rest of the model if they are too small.

**Minimum embossed feature size**

**Z Layer features**
- **H:** 0.10 mm (0.004")
- **W:** 0.80 mm (0.031")

**Horizontal XY features**
- **D:** 0.20 mm (0.008")
- **H:** 0.80 mm (0.031")

**Vertical XY features**
- **D:** 0.20 mm (0.008")
- **W:** 0.80 mm (0.031")

An embossed feature is one that is raised above the surface of the model. Common examples include lettering and texture. Embossed features may blend into the rest of the model if they are too small.

**Important note:**
- Avoid printing posts with heights (H) more than five times their diameter (D). All posts are more susceptible to shear on layer lines. If you do print posts, ensure that H ≤ 5D.
- To prevent gaps on features less than 2 mm (0.078") wide, design embosses to be even multiples of 0.4 mm (0.016"), the width of a single extrusion of plastic.
Quick Reference Sheet (Desktop/Industrial)

Fiber

Minimum fiber reinforcement feature width

<table>
<thead>
<tr>
<th>Feature</th>
<th>Open feature</th>
<th>Looped feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>3.6 mm (0.15&quot;)</td>
<td>2.8 mm (0.11&quot;)</td>
</tr>
</tbody>
</table>

Minimum fiber reinforcement part height

<table>
<thead>
<tr>
<th>Material</th>
<th>Fiber Groups</th>
<th>Minimum Reinforceable Height (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass, HSHT, Kevlar®</td>
<td>H: 0.9 mm (0.035&quot;)</td>
<td>H: 1.125 mm (0.04&quot;)</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>H: 0.9 mm (0.035&quot;)</td>
<td>H: 1.125 mm (0.04&quot;)</td>
</tr>
</tbody>
</table>

Minimum fiber length

L: 45 mm (1.77")

Sometimes holes are too small to reinforce with a given number of concentric fiber rings. Here are the minimum hole sizes for 1-3 rings of fiber.

<table>
<thead>
<tr>
<th>Rings</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three rings</td>
<td>D_3: 0.5 mm (0.020&quot;)</td>
</tr>
<tr>
<td>Two rings</td>
<td>D_2: 3.85 mm (0.152&quot;)</td>
</tr>
<tr>
<td>One ring</td>
<td>D_1: 12.16 mm (0.479&quot;)</td>
</tr>
</tbody>
</table>

Smallest reinforced area

Area: 90 mm² (0.14 in²)

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass, HSHT, Kevlar®</td>
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</tr>
<tr>
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<td>D_3: 0.5 mm (0.020&quot;)</td>
</tr>
</tbody>
</table>

This minimum strand length (L) can materialize in a few ways but must also meet the reinforcement width criteria.
**Fiber**

Minimum fiber reinforcement feature width

<table>
<thead>
<tr>
<th>Feature</th>
<th>Open feature</th>
<th>Looped feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>W:</td>
<td>3.85 mm (0.152&quot;)</td>
<td>2.9 mm (0.114&quot;)</td>
</tr>
</tbody>
</table>

**Minimum fiber reinforcement part height**

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>fiberglass, HSHT, Kevlar®</th>
<th>Carbon Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>H:</td>
<td>0.9 mm (0.035&quot;)</td>
<td>1.125 mm (0.044&quot;)</td>
</tr>
</tbody>
</table>

**Minimum fiber length**

L: 58 mm (2.283")

Sometimes holes are too small to reinforce with a given number of concentric fiber rings. Here are the minimum hole sizes for 1-3 rings of fiber.

- **Three rings**
  - D_3: 2.9 mm (0.114")
- **Two rings**
  - D_2: 6.1 mm (0.240")
- **One ring**
  - D_1: 17 mm (0.669")

This minimum strand length (L) can materialize in a few ways but must also meet the reinforcement width criteria.
Identifying 3D Printing Opportunities

When should you print with continuous fiber?

Continuous Fiber Fabrication is unique in that you can selectively increase the lifetime of a part. Fibers strengthen the part far beyond traditional plastics, meaning a reinforced part can hold up much better over an extended period of time than a standard plastic part.

Determine material needs and behaviors

Consider the material requirements of your part.

- How strong or stiff does it need to be?
- What environment will your part be in?
- How many cycles does it need to last?
- How much can it weigh?

Use these considerations to select a material that suits the part.

Cost considerations

Turn to 3D printing when the costs of traditional manufacturing are prohibitively expensive for your needs. 3D printing is often appropriate for low- to mid-volume applications, but for a given part there is always an inflection point at which other manufacturing methods become more cost-effective. Compare cost-per-quantity values to discover this tipping point.

Time analysis

3D printing allows for rapid iteration so you can test out new designs quickly. Continuous fiber reinforcement facilitates strong parts for work-like prototypes and end-use that you can improve print-by-print and implement in a matter of days. Look for opportunities to cut down on lengthy lead times with additive manufacturing.

Calculate ROI

Use ROI calculations to justify which parts or subassemblies will benefit from 3D printing. Upload your parts to Markforged's Eiger software to get the material cost and print time, and compare this to estimates from other manufacturing platforms. This should give you a sense for the time and cost savings involved in creating your part.

Metal strength

7KHVWUHQ1WKRIDÆEHUULQIRUFHG5HLQIRUFLO,JÆHUVFDQYDVW01 part comes from the combined strength of the plastic and the FRQWLQXRXVÆHUVWUDQGVZRHYQ throughout the part. This can make parts comparable to aluminum in VWWUHQ1JKDQGVWLVQHVV

Durability

5HLQIRUFLO,JÆHUVFDQYDVW01 increase the lifetime of a part. Fibers strengthen the part far beyond traditional plastics, meaning a reinforced part can hold up much better over an extended period of time than a standard plastic part.

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What to Consider When Printing

As you design your part, consider how it can be optimized for the layer-by-layer printing process. Below are six considerations to keep in mind when designing your parts:

1. Determine loading conditions

Composite 3D printed parts are stronger on planes parallel to the print bed, especially if you are reinforcing with continuous fibers. Analyze how your part will be loaded and design the part such that the largest forces traverse the XY plane. Some parts may need to be split into multiple printed pieces to optimize for strength.

2. Identify critical dimensions

3D printers have higher precision in planes parallel to the build plate. What are your critical dimensions or features? Critical features print optimally when in plane with the print bed.

3. Maximize bed contact

Greater surface area on the print bed minimizes supports and improves adhesion. Which face of your part contacts the bed? Try to orient the part so that the largest face lies on the print bed, unless strength or geometry needs dictate otherwise.

4. Reduce supports and improve overhangs

Fewer supports reduce printing and processing time. How can you design to minimize supports? Are the supports in your part accessible? Use angled overhangs to reduce supports and improve support removal.

5. Fillet or chamfer edges

Filletting edges normal to the print bed reduces the potential for warping, while chamfering edges flush with the build plate makes part removal easier and prevents edges from splaying on the first layer. Chamfers on interface edges like holes will help line up fits more easily.

Units: mm

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version 1.7
6. Consider printer bandwidth

Consider when you use your printer and how to make efficient use of its bandwidth. Print longer jobs overnight and shorter jobs during the day. You can also create builds by printing multiple parts together that start and end during a workday. Here is a table of guidelines and four example days of prints to help you:

<table>
<thead>
<tr>
<th>What to Consider When Printing</th>
<th>If print time is...</th>
<th>Then kick off at...</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WRKU;GD</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>WRKU;GD</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>WRKU;GD</td>
<td>V</td>
</tr>
</tbody>
</table>

**Example 1: Ideal**

<table>
<thead>
<tr>
<th>Start of workday</th>
<th>9 am</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>16 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>1 uptime</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Example 2: Ideal**

<table>
<thead>
<tr>
<th>Start of workday</th>
<th>9 am</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>20 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>1 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>1 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>1 hr</strong></td>
<td></td>
</tr>
<tr>
<td>**End of workday</td>
<td>5 pm</td>
</tr>
</tbody>
</table>

**Example 3: Non-Optimal**

<table>
<thead>
<tr>
<th>Start of workday</th>
<th>9 am</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>2 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>1 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>13 hr</strong></td>
<td></td>
</tr>
<tr>
<td>**End of workday</td>
<td>5 pm</td>
</tr>
</tbody>
</table>

**Example 4: Optimized**

<table>
<thead>
<tr>
<th>Start of workday</th>
<th>9 am</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>4 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>2 hr</strong></td>
<td></td>
</tr>
<tr>
<td><strong>3 hr</strong></td>
<td></td>
</tr>
<tr>
<td>**End of workday</td>
<td>5 pm</td>
</tr>
</tbody>
</table>
Strategic 3D Printing Design Practices

8

### Splitting up parts

Sometimes it is more effective to split up a part than to print it as one piece. This part is split in two, with each piece printed from its highlighted face to prioritize the strength of each segment. Here are some reasons to consider splitting a part up:

- Parts with many iterations or customizations can be designed with a core base geometry and interchangeable modules
- Elements of parts that undergo increased wear or strain can be isolated into components that can be changed out regularly
- Designs requiring specific strength profiles across multiple axes can be printed in sub-components in different orientations and joined post-print
- Complex prints with critical features on multiple planes can be split into sections to reduce supports, decrease print time, and ensure print success

Think critically about which aspects of your design need to be 3D printed. Some features could be implemented more efficiently with other manufacturing methods. When appropriate, integrate other parts into your design to save on print time and cost or to improve important features. Below are a few examples of where simple hardware integrations can improve part success.

#### Threads and inserts

![Threads and inserts](image)

Where you need threads. These inserts get pressed in with a soldering iron to...

#### Wear surfaces

Dowel pins provide a hardened steel wear surface for areas of parts that interact with...coupling. The dowel pins prevent the threads from cutting into the printed plastic, increasing the lifetime of the grippers.

#### Alignment

![Alignment](image)

Use pressed-in dowel pins or shoulder bolts to precisely align multiple components. Press-fit dowel pins are used to line up this handle with its baseplate, while screws secure it. Use dowel pins for alignment before glueing or bolting the components together to attach multiple printed parts precisely.

#### Concentricity

![Concentricity](image)

Bushings or sleeve bearings like the ones inserted into this bracket provide high cylindrical precision and smooth concentric clearance fits. Off-axis loads distribute to the printed part with the bushing's larger surface area. The bushing can be reinforced with continuous strand composite fibers for higher torsional resistance.

#### Splitting up parts

6

Part is split in two, with each piece printed from its highlighted face to prioritize the strength of each segment. Here are some reasons to consider splitting a part up:

- 3D printed base geometry and interchangeable modules
- Elements of parts that undergo increased wear or strain can be isolated into components that can be changed out regularly
- Complex prints with critical features on multiple planes can be split into sections to reduce supports, decrease print time, and ensure print success
Use unit tests to validate geometries and save print time

In software development, a unit test is used to confirm that a small section of code works before its integration into a larger program. 3D printed unit tests work much the same way. A 3D printed unit test is a small test print that confirms feature success before committing to a long, costly print.

Unit tests can be designed to experiment with different clearances and select the fit most appropriate to your application. Isolate the critical segments of large parts and print multiple versions with slightly altered dimensions or configurations to test how they interface. Update your final CAD model with the specification you find works best, and print it with confidence in its success.

Below are some recommended fits between printed parts. Specifics may change based on material and geometry. Listed dimensions are diametral, indicating the overall change in dimension between the two interfacing parts.

### Tutorial: Designing a unit test

1. Identify critical features in your CAD model that either require tolerance verification or need to be tested to confirm they print as expected.

2. Isolate features in question DVDSDUW\$DHUERV\WHDW\$H\$W the main CAD model. Try to make it a small section that can be printed quickly — aim for under an hour in print time.

3. Design segment variationsL \$RXZDQW\WVRWH\$VGL ‘HUGHOW tolerances on the feature in question. Each unit variation can be its own print or you can combine them into a single part to keep them organized.

4. Print and test segment variations to determine which variation $BWKWHZD\$RXOLNHLWDQGEHWWXLW\$RXUSDUWQHGV

5. Update the original model with the desired dimensions tested with your variations and print out the full part.

### Tolerancing and clearances

<table>
<thead>
<tr>
<th>Fit Type</th>
<th>Dimensions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close fit</td>
<td>0.05 mm - 0.10 mm (0.002&quot; - 0.004&quot;)</td>
<td>Parts require some applied force via cold pressing to assemble.</td>
</tr>
<tr>
<td>Free fit</td>
<td>0.10 mm - 0.20 mm (0.004&quot; - 0.008&quot;)</td>
<td>Parts can slide and/or rotate easily when assembled.</td>
</tr>
</tbody>
</table>

Diametral clearance = A - B
Understanding Matrix Materials

Types of matrix materials

Designing for Onyx FR

Reducing afterflame time with Onyx FR:

1. Feature size: Ensure that features such as holes, cutouts, and thin sections are at least 3 mm thick. Smaller features may require external treatment to ensure flame retardancy.

2. Walls and infill: Increase the wall thickness and density of the infill to distribute heat and smoke more effectively. This can help to reduce the afterflame time.

3. Fiber reinforcement: Use fiber-efficient reinforcement practices to place continuous fibers where you need strength to limit the afterflame time. Optimize the fiber volume to balance strength and flame retardancy.

Markforged matrix materials are chemically resistant and reinforceable with any continuous fiber options. A composite material is a combination of two materials that, when combined, create a material to leverage benefits of both of its constituents. Each constituent material is distinct within the composite, so a mixture is not considered a composite material. Markforged 3D printers print in composites by laying continuous fibers into a plastic matrix material. By combining the surface and chemical properties of the matrix material with the strength, stiffness, and failure behavior of a fiber, you can create a composite 3D printed part optimized for the environment and the application you need.
Diving Deep into Fiber Reinforcement

Types of fiber

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Properties</th>
<th>Ideal Loading Type</th>
<th>Failure Behavior</th>
<th>Characteristics and Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fiber</td>
<td>High strength-to-weight ratio, stiff</td>
<td>Constant loading</td>
<td>6WŁ`QXWLOIUDFWXUH</td>
<td>0HWDOVWL`QHVVDQG strength, lightweight</td>
</tr>
<tr>
<td>fiberglass</td>
<td>Sturdy, cost-effective</td>
<td>Intermittent loading</td>
<td>%HQGVXQWLOIUDFWXUH</td>
<td>Economical starting point, JHQUD0XVHÆEHU</td>
</tr>
<tr>
<td>HSHT fiberglass</td>
<td>High energy absorption until fracture</td>
<td>Constant loading</td>
<td>%HQGVXQWLOGHIRUPDWRQ</td>
<td>Keeps strength at high temperatures</td>
</tr>
<tr>
<td>Kevlar®</td>
<td>High deflection and impact resistance</td>
<td>Impact loading</td>
<td>+LJGHIHWLRQDGQGLPSDFW</td>
<td>+LJGHIHWLRQDGQGLPSDFW resistance</td>
</tr>
</tbody>
</table>

Types of fiber fill

Concentric Fill

This type only reinforces the outer walls of a part. This can be used to reinforce the part for bending or impact loads applied to the sides of the part.

Isotropic Fill

This type only reinforces the inside walls of a part. This can be used to strengthen bolt holes or cavities to improve load distribution when FRPSUHVLYHRURXWRIKDLYVRUVRQDO forces are applied to inner holes.
A brief composites fiber lesson

Imagine you are holding a piece of raw spaghetti by one of its ends. Under which type of load is it strongest? If you try to bend it, it snaps. If you try to compress it lengthwise by trying to push the two endpoints closer together, it also snaps. However, if you load it in tension by pulling on it, it can hold a decent load.

This is the theory behind working with continuous composite fibers. Whether you are printing them, winding them, or weaving them, continuous fibers are strongest when loaded in tension. Composite fiber materials like carbon fiber, Kevlar®, and fiberglass are known for their material properties in tension. The key is understanding where the fibers are loaded in tension, and how a given load can distribute amongst the local fibers.

Tension

Fibers are strongest in tension, so a part loaded in tension should consist of fibers running up and down the length of the part, being "stretched" by the force. You can align fibers with your tensile forces with CONCENTRIC FIBER along ribs or with FIBER ANGLES when using ISOTROPIC FIBER.

Bending

Beam Bending Theory shows that when a beam is bent, the inside face of the bend is loaded in compression, while the outside face of the bend is loaded in tension. By putting rigid materials on the extremes of a beam you reinforce it most effectively. This is why traditional composite layups consist of fiber panels on each face with a softer material on the inside, forming what is called a sandwich panel. To reinforce a part in bending, build a sandwich panel with ISOTROPIC FIBER panels if the neutral plane is in XY, or CONCENTRIC FIBER when bending around the Z axis.

Compression

The key to dealing with compressive forces is in the force distribution. The fiber should serve as a scaffold beneath the load, able to distribute the load along the fiber's path. Side loads can be reinforced from compression with CONCENTRIC REINFORCEMENT. Vertical loads can be reinforced from compression using ISOTROPIC REINFORCEMENT on the upper and lower faces, and CONCENTRIC REINFORCEMENT between the two isotropic panels to further support the load. This is especially helpful for supporting clamping forces from bolts.

Important note:

Markforged 3D printers print composite parts that are effectively transverse isotropic. While isotropic materials have uniform material properties in all directions, transverse isotropic materials have one set of properties along an axis, and a different set on planes normal to that axis. This translates to 3D printed parts, in which the part strength on XY planes is stronger than the part strength along the Z axis, especially with continuous fibers. This is why it's important to consider print orientation during the design process.
How to think about reinforcing with continuous fibers

1. Identify loading conditions

Does fiber fit and travel through the areas you need it to? Can you trace continuous strands of fiber that route along the load paths and "brace" against the force? If not, you may need to adjust fiber settings or modify features so that fiber runs through the places you need it to. Remember that fiber groups requires at least four plastic roof and floor layers to print, so any faces that need reinforcement should start four layers offset from the closest roof or floor.

2. Determine print orientation

Take a look at your design. Where will it undergo bending forces? Tensile forces? Compressive forces? If you're not sure, think about how forces will transmit through other parts — draw a diagram if you need to! This will help you to make an informed decision about your fiber routing strategy.

3. Determine reinforcement areas

Based on loading conditions, what surfaces or segments need to be strengthened? With that in mind, think about what types of reinforcement you will need to implement in those areas.

4. Balance fiber panels

If only one side of a part is reinforced, it may be prone to warping due to an uneven sandwich panel — if one face is strengthened and the other isn't, or if one face has a vastly different cross-section. If one layer group of your part is reinforced, balance the sandwich panel by reinforcing an equivalent layer group on the furthest substantial Z layer with a similar cross section.

5. Confirm fiber pathing

Does fiber fit and travel through the areas you need it to? Can you trace continuous strands of fiber that route along the load paths and "brace" against the force? If not, you may need to adjust fiber settings or modify features so that fiber runs through the places you need it to. Remember that fiber groups requires at least four plastic roof and floor layers to print, so any faces that need reinforcement should start four layers offset from the closest roof or floor.
Basic reinforcement strategy: Shelling

Outlined below is a basic strategy for reinforcing a printed part. This strategy will ensure your part is generally strong and resistant to bending and impact forces on any axis. As described earlier, it’s more important to reinforce the extremes of your part than the core, so we are going to walk you through how to “shell” a part for efficient strength all around.

1. Isotropic panels on furthest substantial Z layers

Add 2-4 layers of **ISOTROPIC FIBER** on the top and bottom planes of the part, excluding any small surface extrusions. The fiber layers should start above the four “floor” layers or end below the four “roof” layers of a given horizontal surface.

2. Isotropic panels on intermediary large geometry changes

Add 2-4 layers of **ISOTROPIC FIBER** below or above any surfaces that dictate large changes in part geometry, again accounting for four “roof” and “floor” layers.

3. Inner hole reinforcement for Z-axis bolt holes

Reinforce Z-axis bolt holes with two rings of **CONCENTRIC FIBER**. Use **INNER HOLES ONLY** if you don’t need side load reinforcement, or use **ALL WALLS** to encompass Step 4. This will distribute the compressive force applied by the bolt and creates a composite “sleeve” to resist any off-axis torsional loads the bolt experiences.

4. Outer-wall reinforcement for any side loads

To maximize bending strength about the Z axis and reinforce against side loads, reinforce the outer walls of the part with two rings of **CONCENTRIC FIBER**. Use **OUTER SHELL ONLY** if you have no Z-axis bolt holes, or use **ALL WALLS** to encompass Step 3. This will also reinforce any holes with axes on the XY plane.

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**Diving Deep into Fiber Reinforcement**

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Specialized reinforcement strategies

Fiber panel striping

For increased bending strength on the XY plane, you can add "stripes" of ISOTROPIC FIBER across multiple Z layers. This is most effective with thicker parts that have a fairly consistent or symmetric cross section, because Fiber striping creates multiple superimposed sandwich panels to further reinforce a part in bending.

If you need to address more specific loading conditions, you can employ different tactics to strengthen specific areas, reinforce certain part sections, or control fiber placement. Below are some unique additional strategies you can implement inside your part.

Diving Deep into Fiber Reinforcement

Achieving Z-axis strength

Clever design and reinforcement strategies allow you to achieve greater strength on multiple axes. Running a bolt through your part with fiber reinforcing the compressed surfaces can strengthen the part and prevent shear or tensile forces from splitting the part on layer lines. You can reinforce the area around the bolt with CONCENTRIC FIBER — INNER HOLES ONLY so that any of those forces distribute to the fiber in the form of bending forces.

Directing fiber with ribs

You can route fiber in specific directions with reinforced ribs or cutouts that follow load paths from forces applied to your part. You can force the fiber to follow these load paths by applying CONCENTRIC FIBER to reinforce around the cutouts or walls.

Using fiber angles to direct fibers

You can use the FIBER ANGLES tool to route the "zig-zag" of Isotropic Fibers in a certain direction. If you have the fibers routed in a specific direction to better align with the forces being applied to your part, you can manipulate the angle of this pattern. The default Angles dialog box for any layer, any group of layers, or across the entire part.

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Maximizing Print Success

Markforged Precise PLA has been developed to meet the design guidelines of Onyx parts. Design recommendations in the Quick References section of this guide should be referenced. P-PLA is an ideal prototyping material for visual-only applications, lacking the impact resistance and durability of Onyx. The following guidance is intended to maximize the printing success of P-PLA parts. Please note that P-PLA is not compatible with Continuous Fiber Reinforcement.

Printing with Precise PLA

Stability

Avoid long and narrow parts. When material cools, the part contracts lengthwise. Avoid long and narrow parts to optimize the quality of your printed part.

Add fillets on the outer corners in the XY plane

Design with round, natural shapes in mind. Sharp corners are where stress concentrates the most, causing them to lift. To avoid this, add fillets on the outer corners in the XY plane. Rounded edges will reduce stress concentrations.

Integrate a brim in the design

Sharp corners are the most common geometries that warp. Add thin brims of 0.2mm to 0.4mm at the part’s base to distribute built-up stress. The brims should be at least 20mm in diameter to each corner. The added brims will increase the part’s footprint and anchor the corners of the part. Thin brims are easily removed from a printed part.

Bed Adhesion and Warping

1. Avoid long and narrow parts

2. Add fillets on the outer corners in the XY plane

3. Integrate a brim in the design

Stability

Avoid long and narrow parts. The taller a part, the greater its chance of shifting from a collision with the plastic nozzle. Avoid tall and narrow parts.

Always make sure to apply glue to the print bed before printing. It is important to apply two layers of glue to the print area to anchor the corners of the part. Thin brims are easily removed from a printed part.

Fine Features
Smooth TPU 95A Design Principles

**Quick Reference Updates**

**Part Compliance**

Smooth TPU parts can noticeably change compliance as you vary the Eiger settings for Fill Density, Wall layers, and Floors. Adjusting these settings can result in different flexural modulus and Shore hardness for S-TPU parts. Example: By changing a part's settings from Default to Gyroid Infill with 20% Density, the resulting part will be more flexible (more compliant).

Part geometry can also significantly impact compliance. The primary method of increasing part compliance by altering geometry includes placing “cuts” in parts, or replacing bulk geometry with thin walls, that allow the part to bend, twist, stretch, and compress further.

**Material Specific Considerations**

**Fine Features and Stringing**

Smooth TPU is prone to “stringing”: excess material oozing from the nozzle and unintentionally depositing on the part. Parts with many fine features require more prime/retract moves leading to an increase in stringing. For optimal part quality, try to minimize the amount of fine features on your designs. Avoid fine features (e.g. spikes/columns) with diameters/widths smaller than approximately 2.5mm (0.1in).

**Minimum unsupported overhang angle**

θ: 55°

**Minimum post diameter**

<table>
<thead>
<tr>
<th>XY</th>
<th>2.5 mm (0.1”)</th>
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</thead>
<tbody>
<tr>
<td>Z</td>
<td>2.5 mm (0.1”)</td>
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</tbody>
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