

Short review of nonplanar fused deposition modeling printing

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Abstract

As one of the additive manufacturing (AM) methods, fused deposition modeling (FDM) technology is widely adopted but involves some limitations in lacking surface quality and mechanical properties due to the use of only planar layers. This review will explore the novel FDM approach, curved layer FDM (CLFDM) where a nonplanar slicing technique is introduced to improve on these shortcomings. Recently, this technique has gained more and more traction in the industry and among consumers owing to not only its great potential to overcome several manufacturing limitations of conventional FDM method such as the “staircase effect” and poor bonding strength of curved surfaces or shells but also enhanced mechanical properties of CLFDM printed parts. The present review mainly focuses on the toolpath generation, process adaptations, mechanical properties of the printed part, and novel applications in the CLFDM method.

KEYWORDS

additive manufacturing, mechanical properties, surface roughness

1 | INTRODUCTION

1.1 | FDM printing

Layered manufacturing (LM) is a fabrication method where parts are manufactured by deposition of material layer by layer. LM is often referred to as rapid prototyping (RP) because it reflects one of the most common uses. One major benefit of LM is the “direct” fabrication capability due to it being an additive manufacturing process. This relaxes the requirement for special tooling and setups for fabricating parts.¹

Fused deposition modeling (FDM) is an LM process where a continuous thermoplastic filament is deposited onto a build surface to construct a part. The process is shown schematically in Figure 1. The extruder nozzle deposits filament paths in a raster pattern to build a solid layer. The part is built by stacking these layers in the z -direction.

1.2 | Imitation of traditional planar FDM printing

In FDM, the toolpaths, for the 3D printer, are derived from the 3D model of the part geometry. This process, from 3D model to printer toolpaths, is not perfect and involve some intrinsic errors. Two sources of error occur at different stages

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of the conversion process. Figure 2 gives an overview of this process and shows the steps where the errors are introduced. First, a tessellated (STL) version of the 3D model is exported by CAD software. In the second step, during slicing, the model is sliced in a stair-stepping way by a set of horizontal planes intersecting the geometry. Each intersection gives a polygon representing the contour of the part for that plane. The laminar contours can be stacked to represent the part. This reflects how parts are made in FDM and LM. The process of extracting the contours for each layer is called slicing and performed by a routine or program called a slicer.

In the first conversion step, when the 3D model is tessellated, an approximation is made with a triangle mesh. This process gives the first intrinsic error. A chordal error is originated from approximating curved regions with a mesh of planar triangles because the meshed model does not completely coincide with the 3D geometry.² The second source of error occurs in the slicing step. Conventionally, the planar horizontal slicing is the only solution for three-axis printer to slice models during LM processes. Horizontal slicing introduces a source of error for sloped regions of the part. These regions cannot be perfectly created with planar layers because only a finite amount of them is possible. Due to this, the surface of the final part will have a stair-like artifact which is commonly known as the staircase effect.² The effect is illustrated in Figure 3 for a simple part with a slightly sloped top surface.

The chordal error, during tessellation, can be controlled directly when exporting the 3D model to an STL file. Reducing the chordal error involves increasing the number of triangles in the STL mesh. This gives an accuracy–efficiency trade-off because the slicing routine's complexity increases with the number of triangles.³

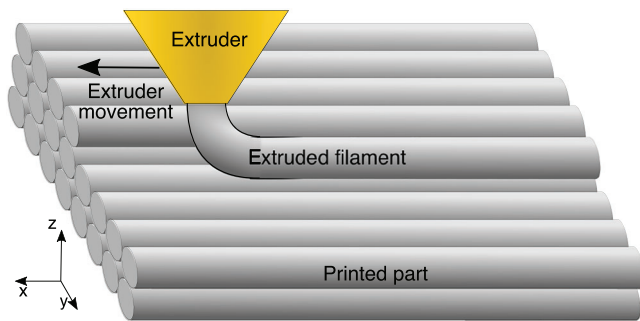


FIGURE 1 Schematic of FDM printing. An extruder deposits a thermoplastic filament onto a substrate in a raster pattern layer by layer to construct a part

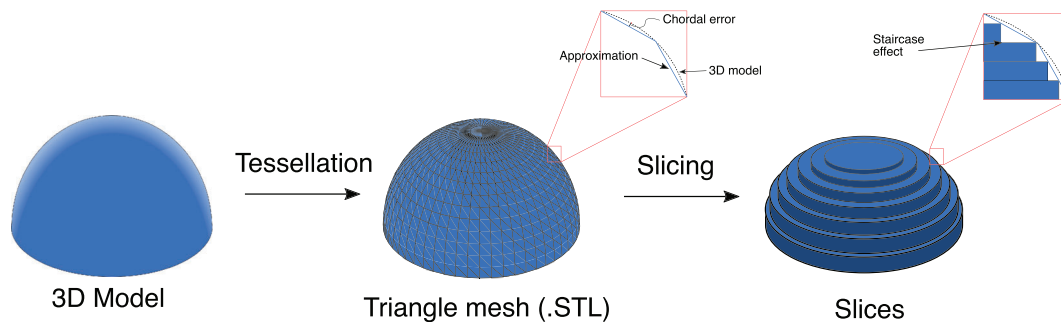


FIGURE 2 High-level steps from 3D model to slicing for the LM process

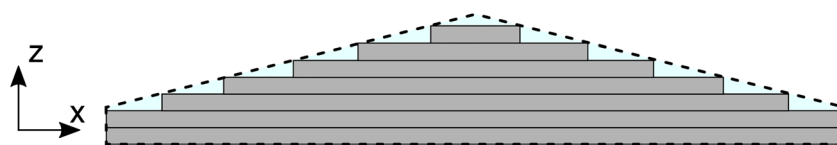


FIGURE 3 Part with slightly slanted top surface fabricated by conventional FDM slicing method. The dashed line represents the geometry from CAD. The solid gray rectangular bars represent the planar extrusions from the FDM process. The staircase effect is the blue triangular area

1.3 | Approaches to overcome the limitations

Mitigating the staircase effect is more difficult due to it being intrinsic to LM processes and conventional planar FDM printing.³ Different methods have been attempted to mitigate the staircase effect. Refining the layer thickness is one way to reduce this error. The effect of this is shown in Figure 4. Refining the layer thickness gives a trade-off between part accuracy and print time (printing efficiency). Slicing a part into thinner layers increases the total extruding path length and thus longer printing time.

When slicing a part, the slice thickness can be controlled by the operator to mitigate the staircase effect. A constant slice thickness can be set for the entire part. Refining the slice thickness globally, without considering local geometry, is a naïve approach that neglects geometric information contained within the model.⁵ Some regions can be approximated well enough with thicker layers while some require thinner layers. The process can be optimized this way by only using thinner layers where needed.

A method called adaptive slicing seeks to adapt the slice thickness depending on local geometry and reduce the print time while still retaining part accuracy.⁶ With this method, the extent of the staircase error can be controlled by a user-specified tolerance. This is usually the chordal error for each “stair-step.” In regions with small surface angles to the horizontal plane, the layer thickness is decreased to keep the staircase error within tolerance. Where the surface angles are larger, thicker layers can be used. Utilizing the geometrical information means that higher-quality prints become more efficient.

Recently, curved layer FDM (CLFDM), also known as curved slicing, has received increasing interest from scientists and engineers to mitigate or completely remove the staircase effect by creating toolpaths that follow the geometry of the 3D model. This removes the restriction of only having planar slices. Printing of thin shells is a good example where CLFDM greatly improves the surface quality of the part. Figure 5 shows schematically the difference between CLFDM and standard FDM for a thin shell. In Figure 5A, only planar layers are used, as with standard FDM. In Figure 5B, the toolpaths are adapted to the curvature of the shell, as with CLFDM. By using CLFDM as in Figure 5B, the staircase effect can be eliminated, and therefore, a much better geometrical accuracy and surface quality could be attained. The finished part will also consist of longer continuous printed paths.

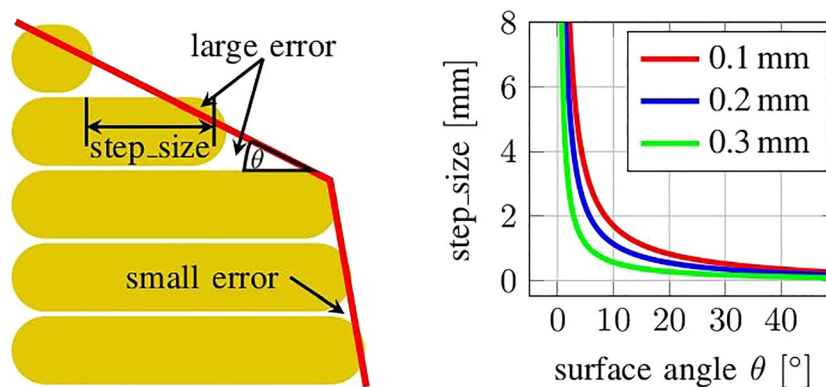


FIGURE 4 Quantitating the staircase effect. Larger surface angles create larger errors. For slightly sloping surfaces, the error becomes large. The graph shows error for 0.1-, 0.2-, and 0.3-mm layer height⁴

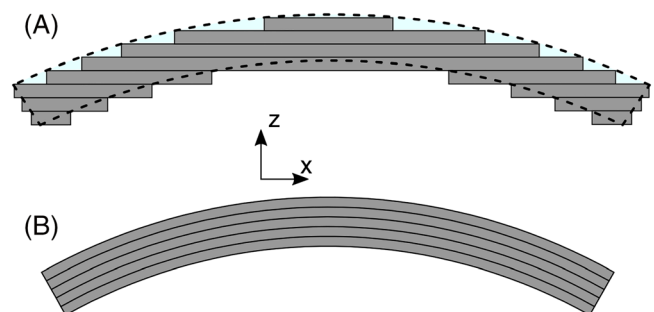


FIGURE 5 Thin shell fabricated with (a) only planar layers and (B) with CLFDM where the extrusions are adapted to the geometry of the part. The dashed line represents the geometry from CAD. The gray rectangles are the planar extruders/printed path. The result is longer continuous filaments that follow the shell curvature

2 | WORKING PRINCIPLES OF CLFDM

CLFDM is still in its early stage, so methods for generating toolpaths have not been completely established. Thus, researchers and scientists are interested in developing novel routines to generate nonplanar toolpaths and methods for improving the generated toolpaths. In this section, we will look at how these routines have evolved and been adapted to face the challenges of CLFDM.

2.1 | Parametric surfaces

Chakraborty et al⁷ were the first to introduce curved layers into FDM printing. In the first paper implementing curved layers for FDM printing, the author used parametric surfaces to represent printable shells and suggested algorithms to generate toolpaths along this surface.⁷ Issues regarding CLFDM for three-axis machines and adjacent filament overlap were presented in the paper as well. This will be further discussed in Section 2.3.

In another paper by Allen and Trask,⁸ the authors manufactured sandwich laminates with CLFDM by using parametric surfaces. A method was demonstrated using a planar layered sandwich core and a nonplanar layered skin on top and bottom. As a control, they also printed the same laminate using only conventional planar slicing. Figure 6 shows how the staircase effect is removed by using nonplanar layers for the skin.

Even though parametric surfaces show promising results, it is also a restriction. To print a part with this method a mathematical representation is needed. This is not always possible or feasible for a part with complex geometry. To extend the applications of CLFDM, a method interfacing with CAD is needed.

2.2 | STL CLFDM slicing

Traditionally, STL files are the standard input for FDM printing to generate toolpaths and can be exported by all commercial 3D software. Although it is more challenging to directly use STL files to generate the toolpath for the CLFDM method, there are huge benefits. As a result, scientists and engineers have recently developed several approaches to generate toolpaths using STL slicing.

2.2.1 | Slic3r CLFDM implementation

In a paper by Ahlers et al⁴ an extension of an already openly available slicer, Slic3r,⁹ was created. Slic3r is a free and open-source slicer that turn 3D models into printable G-Code. G-Code is the set of sequential instructions that the printer receives to print a part. It contains toolpath coordinates and the amount of material to extrude.

Natively, Slic3r does not support nonplanar layers. The authors sought to change this and improve the print quality of the slicer. The general idea of the approach was to first slice the model by regular planar slices, which is standard for

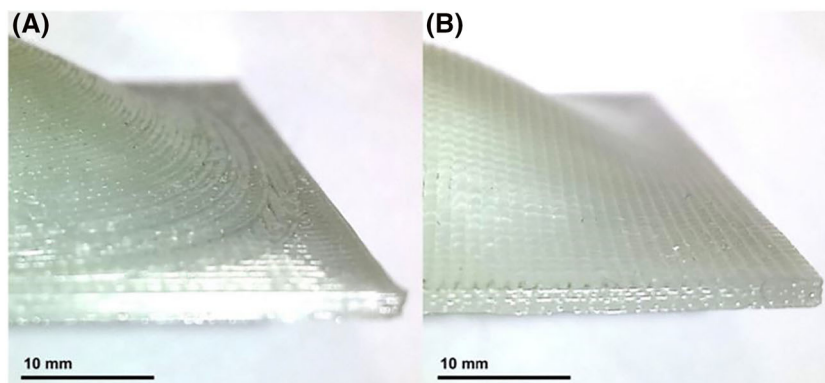


FIGURE 6 Printing of part by (a) FDM compared to (B) CLFDM⁸

Slic3r. Afterwards nonplanar layers could be included by postprocessing the generated planar toolpaths. The method worked by identifying which outer surfaces of the part were suitable for nonplanar printing. To identify the surfaces, the STL mesh was parsed and regions were classified by either being suited for nonplanar printing or not. This was done by comparing each facet normal to a threshold angle. Afterwards, the planar layered structure was modified to allow the printing of nonplanar layers on top. The nonplanar toolpaths were generated and appended to the G-Code instructions.

Appending nonplanar toolpaths to a printing routine introduced the risk of crashing the extruder into the already printed material. The author solved this by implementing an algorithm which traced the toolpaths and checked for interference between the extruder head and already printed material.⁴ Figure 7 shows the result of this approach. By printing nonplanar layers on top of a planar layered structure, the staircase effect is eliminated.

2.2.2 | Direct STL CLFDM slicing

In a paper by Singamneni et al¹⁰ a more direct approach to CLFDM toolpath generation was described. In this paper, three central issues of CLFDM were discussed: generation of raster infill for curved layers, parallel offsetting of curved slices, and support generation. For the first issue, generating raster infill for curved slices, two methods were proposed. One was using commercial computer-assisted machining (CAM) software. When generating toolpaths for machining with a ball-end mill, the toolpaths closely resemble the raster pattern used in FDM. The CAM toolpaths can be postprocessed and adapted to the FDM process to achieve curved raster patterns. The second method was doing nonplanar slicing by implementing a custom algorithm for parsing and slicing STL files. It was deemed that both methods could act as a starting point for generating CLFDM toolpaths, but the second method gave a more fundamental approach and allowed for greater freedom as you do not need commercial CAM packages.¹⁰

The second issue discussed by Singamneni et al¹⁰ was generating parallel curved slices. The basic approach to this is only offsetting every point in the z -direction by an amount equal to the layer thickness. This method has shortcomings in that local variations of the curved layers are not captured. The authors proposed another method to mitigate this issue by considering the local geometry of the part and preserving it after offsetting.

In a later paper by Huang and Singamneni,¹¹ another curved slice offsetting algorithm was proposed where each individual triangle of the mesh was offset one by one. This process creates gaps between the triangles of the mesh. The generated gap can be closed by identifying neighboring triangles and reconnecting the points on those neighboring triangles.¹¹

The third issue discussed was generating support structures for the nonplanar laminate. This was solved by initially printing a structure with planar layers, for the support, and then printing the nonplanar layers on top. The geometry of the support was extracted by using the bottom-most nonplanar layer and slicing it with planar layers. The nonplanar laminate can then be built upon this structure.¹⁰

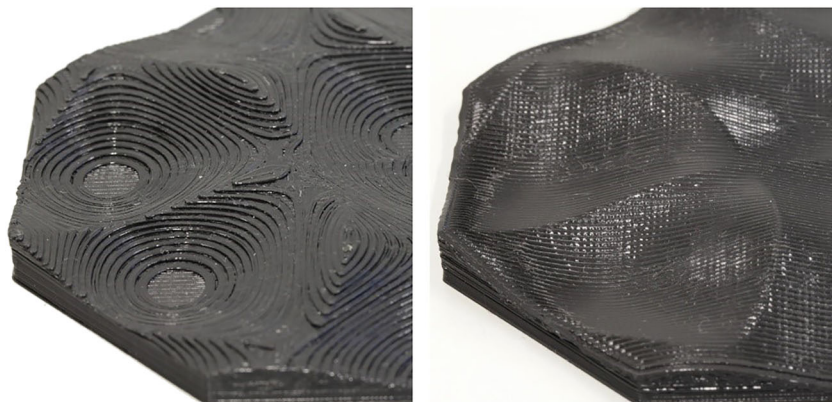


FIGURE 7 Mitigation of staircase effect by implementation of nonplanar slicing in Slic3r⁴

2.2.3 | CLFDM with adaptive layer thickness

To extend the flexibility of the nonplanar slicing algorithm, adaptive slicing can be combined with CLFDM. Huang and Singamneni¹² developed a new slicing method, curved layer adaptive slicing (CLAS), where the layer thickness was varied adaptively throughout the thickness of the model. Adapting the layers creates the ability to mitigate the staircase effect at the free edges of the 3D printed part. The authors demonstrated the algorithm by laminates where the central layers were thicker to reduce printing time but still retain a good surface quality.¹²

2.2.4 | CLFDM with planar layered core

So far, the parts printed have been laminates only consisting of curved layers. To create more complex parts, a mixed approach is introduced. This is presented in Huang and Singamneni¹³ where the exterior was sliced with curved layers to eliminate the staircase effect while flat layers were used for the interior (bulk) material. This combined approach created the possibility to print more intricate parts with the surface quality found in CLFDM. One example they demonstrated was the generation of toolpaths for an aerofoil-like geometry. This is shown in Figure 8. The outer shell was printed with curved layers, and the inner bulk was printed with planar layers. With this method, a more complex part could be created with CLFDM.

2.3 | Process adaptations

Creating nonplanar toolpaths poses additional challenges. Standard three-axis machines cannot rotate the printing nozzle. It is fixed in the “global z -direction.” This causes there to be an angle between the extruder’s axis and the surface normal during the printing of curved surfaces. This is illustrated in Figure 9. When printing from lower to higher, you risk gouging the previous layer, and when printing from higher to lower, you risk gouging the current filament path.

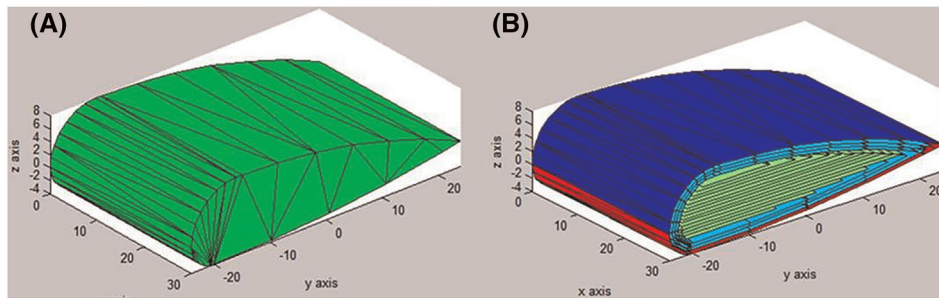


FIGURE 8 Mixed layer approach combining curved layers for the outer shell and planar layers for the inner structure of an aircraft wing geometry¹³

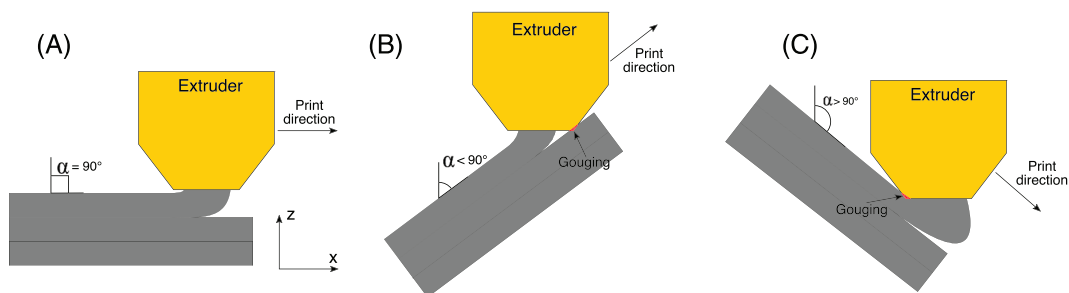


FIGURE 9 Illustration of nozzle interference for standard 3-DOF printer with fixed nozzle. (A) Flat printing involves no interference, (B) lower to higher can involve gouging of previously printed layer, and (C) higher to lower can involve gouging of current layer

This interference will negatively affect the surface quality of the finished part. Process adaptations can be implemented to reduce the risk of this printing defect.¹⁴ We will discuss how later.

Another important parameter in FDM is the spacing between adjacent filament extrusions. Keeping this constant ensures proper and predictable bonding between them. The amount of overlap is closely related to how strong a part turns out.¹⁵ For regular FDM this is done by setting a constant spacing between adjacent filaments. When printing planar layers, the filaments always lie in the same plane, so this means the only variable governing the filament overlap is the path spacing. In CLFDM, extra complexity is introduced because you can have layers that slope transversely to the printing direction. This will influence the overlap between adjacent paths. This is illustrated in Figure 10. Process adaptations need to be made here as well to ensure proper path overlap.

The initial paper on the CLFDM process already discussed the issue of path overlap. A method to ensure proper bonding between adjacent filaments was proposed.⁸ The method adjusts the path spacing to keep the chord of contact constant. The path spacing is adjusted from how much slope there is transverse to the printing direction.

Jin et al¹⁴ seek to mitigate the gouging issue by creating an extra z -offset depending on the local slope in the printing direction. The proposed solution considers nozzle dimensions, the slope of the printing path, and if it slopes upwards or downwards. They also include an additional z -offset for the transverse slope to keep the adjacent path overlap constant.

3 | MECHANICAL TESTING OF CLFDM SPECIMENS

In addition to improved surface quality, CLFDM has also shown promising results considering mechanical properties.

Two papers, Singamneni et al¹⁰ and Huang and Singamneni,¹¹ do comparisons between standard FDM and CLFDM through three-point bending tests. The specimens for comparison are shown in Figure 11 schematically. A schematic of the three-point bending test is shown in Figure 12. In both papers, specimens were printed with standard FDM, as a baseline, and CLFDM. Singamneni et al¹⁰ reported a 40% increase of maximum compressive load for the CLFDM specimen compared to the standard FDM control specimen. Huang and Singamneni¹¹ reported a 51% increase of maximum compressive load compared to the control standard FDM specimen. They also made tests for adaptive flat layer slicing where the bulk of the specimen had thicker layers. They reported a 22% increase of maximum compressive load compared to the FDM specimen.¹¹

Singamneni et al¹⁰ also presented the load versus deflection graphs to show the difference between the mechanical response of the different specimen types. These are shown in Figure 13. The standard FDM specimen showed a more brittle-like failure with load dropping sharply after surpassing the proportional loading region. The CLFDM specimen showed more ductile-like failure with considerable plastic strain after the proportional loading region.

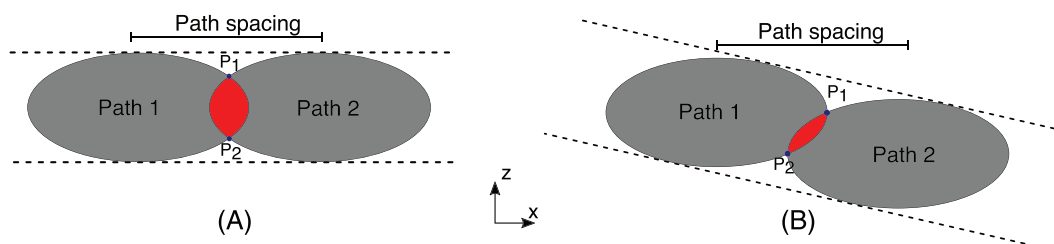


FIGURE 10 Overlap between adjacent filaments with no path spacing adaptations for (a) no transverse slope (baseline) and (b) transverse slope. Increased transverse slope decreases the path overlap area. The distance between P1 and P2 is the chord of contact

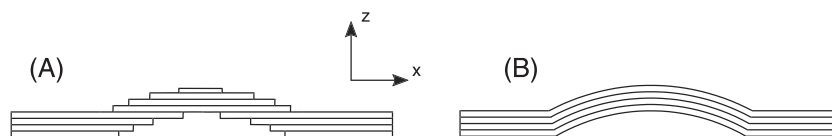


FIGURE 11 Three-point bending specimen printed by (a) standard FDM and (b) CLFDM. The CLFDM specimen has continuous filaments throughout the specimen while the standard FDM specimen has filament discontinuities

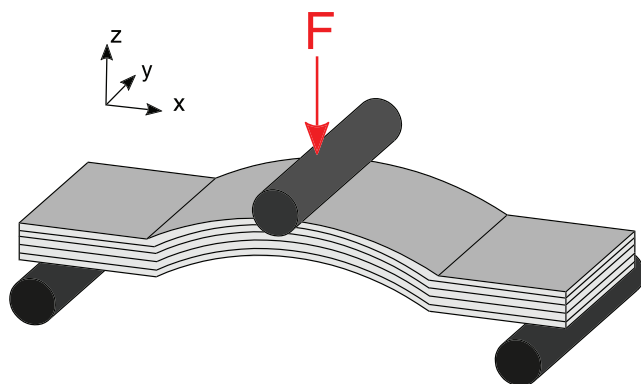


FIGURE 12 Schematic of three-point bending specimen and setup. Layers lines are sketched as for CLFDM printed specimen

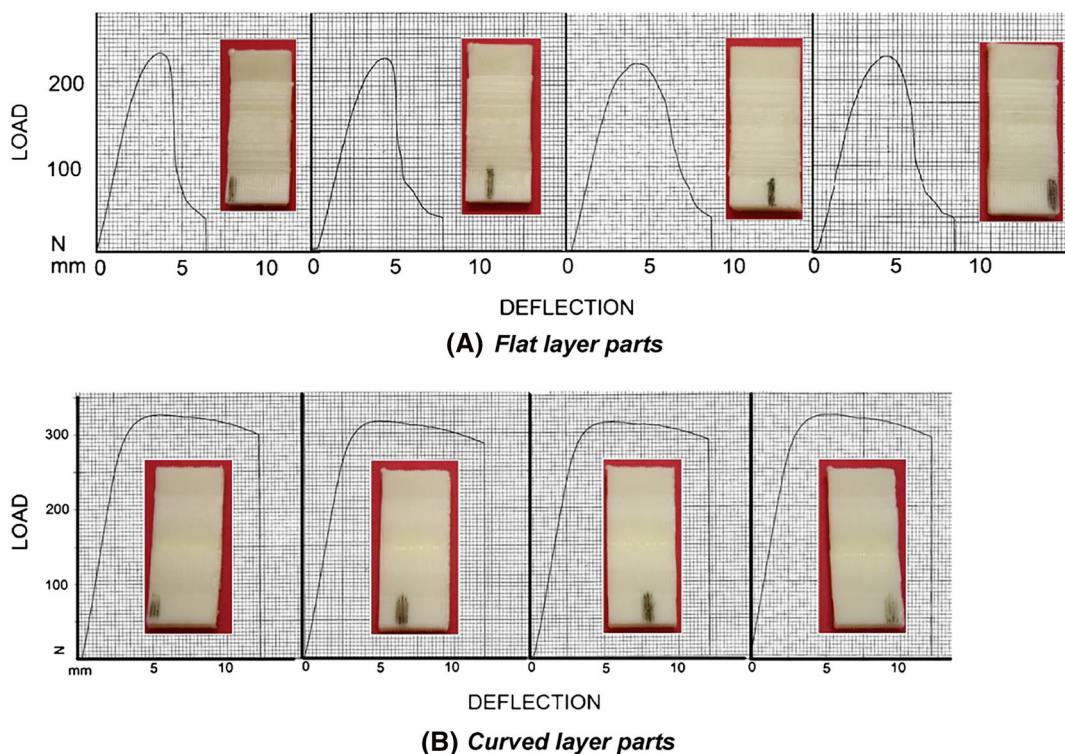


FIGURE 13 Load deflection graph of tensile tests. (A) Planar layered specimen and (B) curved layered specimen

Studies have also been made on the effect of process parameters on the mechanical response of curved layer specimens. Among these parameters are raster orientation, fill gap (overlap between adjacent filaments), and layer thickness through the method of CLAS.

Huang and Singamneni¹⁶ investigated the influence of raster orientation on three-point bending specimens fabricated with CLFDM. The results are shown in Figure 14. It was found that a raster orientation of 0° has the highest flexural load before failure and 90° the lowest. This happens due to the 0° orientation having a preferable arrangement of the filament paths causing them to be equally loaded. As strands get more inclined to the longitudinal direction of the specimen, there will be shear stresses and debonding between adjacent filaments. The 45° raster orientation seemed to break the trend by having a higher flexural load than the 30° specimen. This was likely caused by the increased print time for that exact raster orientation giving a better chance for good coalescence between layers and adjacent filaments.

Guan et al¹⁵ investigated the influence of fill gap on mechanical properties. Fill gap is the spacing between adjacent filament paths. The fill gap was varied between 0.5 to 1.1 mm, with 0.2 mm steps. One-millimeter layer thickness, a 1-mm extruder nozzle, and an extrusion width of apparently 1 mm were used. The testing setup was identical as in Figure 12 with both standard FDM and CLFDM specimens. The raster orientation was 90° . By increasing the fill gap, the peak force before failure was decreased. Figure 15 shows the results. The decrease in peak force with increasing fill

FIGURE 14 Effect of raster angle orientation on the flexural load of three-point bending specimens¹⁶

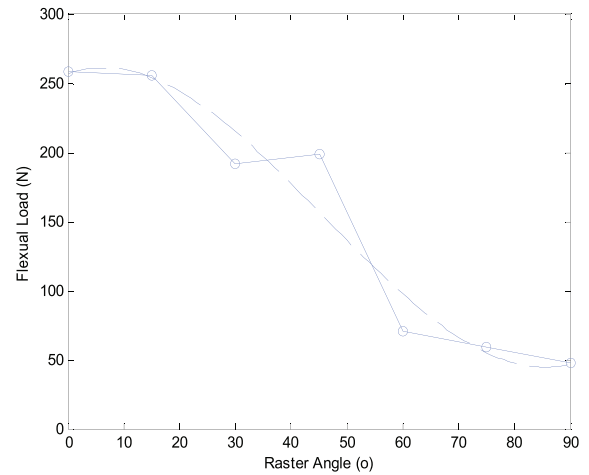
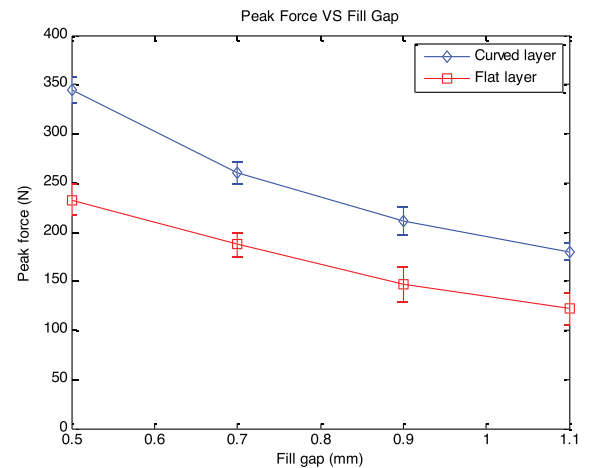


FIGURE 15 Effects of the fill gap on peak force of three-point bending test for the flat layer (FDM) and curved layer (CLFDM) specimens¹⁵



gap was found to be due to the decrease of the bond area between adjacent filaments. They also noted how the CLFDM specimens had about 50% higher failure load compared to the standard FDM specimens for all fill gaps tested. The difference in failure load was attributed to the CLFDM specimens having an increased bond area between filaments. This was shown both by illustrating the process schematically and looking at the finished part through a microscope.

Huang and Singamneni¹² tested the effects of CLAS on three-point bending specimens. They adapted their CLFDM slicing algorithm giving the possibility for using thicker layers in the bulk of the part. The effect of this was that with thicker (and fewer) central layers the failure load got higher. The effect was caused by thicker layers having favorable thermal conditions creating better interfilament coalescence and thicker layers having a lesser chance of discontinuities.

4 | NOVEL APPLICATIONS OF CLFDM

4.1 | Curved auxetic shells

In two papers,^{17,18} auxetic lattice structures printed by CLFDM process are investigated. Auxetic structures are structures that macroscopically exhibit negative Poisson's ratios. The fabrication and testing setup is shown in Figure 16. For curved shells, this can be beneficial as bending stresses are minimized and better distributed across the shell.¹⁷

In McCaw and Cuan-Urquizo,¹⁷ monotonic testing is performed by bending the shell through the normal with a steel sphere. It is found that the shells with auxetic structures, compared to equivalent square-grid, could handle larger deflections before failure. Curved shells fabricated with square grids, instead of curved lines, exhibited bistability also known as “snap-through” behavior. By introducing auxeticity, the bistability problem was mitigated.

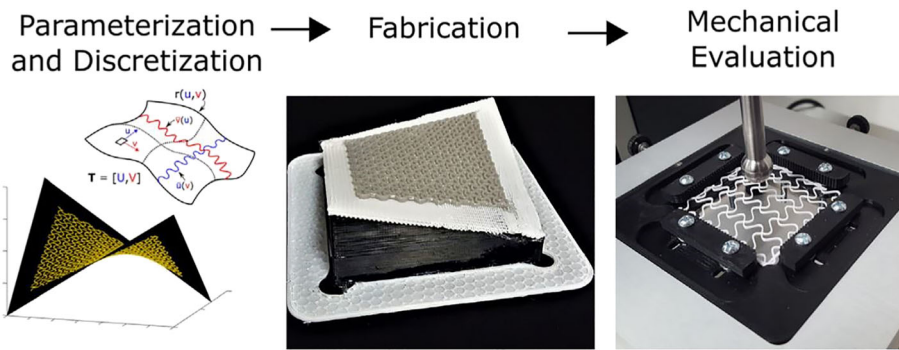


FIGURE 16 Fabrication and testing of curved lattice structures. (Left) Toolpath generation from the parametric surface. (Middle) CLFDM printing of auxetic lattice on top of support mandrel. (Right) Mechanical testing of curved auxetic lattice¹⁷

In McCaw and Cuan-Urquizo,¹⁸ the same type of shells was tested under quasistatic cyclic loading. Higher amplitude (more auxetic) shells showed smaller hysteresis loops and thus dissipated less energy for each cycle. The result is attributed to the auxetic shells having a different mode of deformation and the influence from snap-through (bistability) was avoided.

4.2 | Reuse of support structures

A significant challenge for CLFDM is the dependence of support structures to be able to print the nonplanar layers. For fabricating a simple curved shell, like Figure 3B, a support structure is required as the first layer cannot be printed on a planar build platform. In one example, the support structure can increase the material usage by 1000%.¹⁹

McCaw and Cuan-Urquizo^{17,18} show a way of reusing the support structure by printing a mandrel using fine planar layers. This mandrel is located and glued to the bed of the 3D printer. Creating the mandrel from a different material than the part to be printed ensures the mandrel and part is not fused together. This reuse of support structure provides savings of time and cost by avoiding reprinting the support structure.

In Ramírez-Gutiérrez et al¹⁹ a custom print bed solution was used to be able to adapt the geometry of the bed to the geometry of the CLFDM part. A pin-bed combined with a foam block was used together with custom G-Code to make the printer adapt the geometry of the bed prior to printing nonplanar layers. This way, no support material was needed greatly saving material cost.

5 | CONCLUSION

In this paper, we have explored the research performed on the novel RP method CLFDM. Despite the complex toolpath generation algorithm and the additional modification needed for 3D printer, CLFDM still shows great potential in structural integrity way. Presently, different toolpath generation methods have been continuously developed to generate all kinds of geometry. By using these algorithms, CLFDM printed parts indicate a considerable improvement of flexural strength in three-point bending test and better surface quality based on Singamneni et al¹⁰ and Huang and Singamneni.¹¹ Furthermore, several manufacturing parameters such as fill gaps¹⁵ and raster angles¹⁶ are known to affect the mechanical properties of CLFDM printed part. Nevertheless, the failure mechanism and fatigue performance of the CLFDM printed part are still not clear currently. More researches need to be conducted in the future. On the other hand, the adaption of the extruding system in a common three-axis 3D printer and establishment of a concrete and complex slicing system are two hot trends in the future as well. There are many years of work ahead towards the realization of CLFDM method, novel applications with this method have still long way to go.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study

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