FE modeling of continuous fiber reinforced thermoplastic composite structures produced by additive manufacturing

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Abstract. Additive manufacturing is process of joining material, bringing many benefits such as customization and low production cost. Markforged developed Continuous fiber fabrication technology, which allows to print continuous fiber reinforced thermoplastic (CFRTP) composites. Although printed CFRTP parts achieve mechanical properties better than another 3D printed counterparts, there is demand to gain suitable mechanical properties comparable with conventionally manufactured parts using improvements in printing parameters and fiber deposition. In this paper, the main goal is analyzing of geometry constraints of fiber deposition and modeling options in FEM program ADINA. Additionally, stress distribution analysis with regard to stresses in matrix and fibers will be performed.

1. Introduction
Additive manufacturing is a process of joining materials to make objects from 3D model data layer upon layer, as opposed to subtractive manufacturing methodologies. One of the most widely used additive manufacturing technique is 3D printing. 3D printing contains the fabrication of objects through the deposition of a material using a print head, nozzle or another printer technology [1]. 3D printing includes number of methods; the differentiations between them are based on parameters such as operation principle, printed material, melting temperature etc. The parameters effect to mechanical properties of printed objects [2].

The most widespread printing method is Fused filament fabrication (FFF), which working principle is based on material extrusion process. A thermoplastic filament is fed into printing head where it melts and be extruded out [2]. These processes cause load of fiber and create demand for sufficient quality of fibers [3]. The resolution of FFF is relatively low, because it depends on diameter of extruded fiber [4]. A large number of parameters influence product quality and mechanical properties such as layer thickness, build orientation, feed rate, infill density and others [5].

Each of 3D printing method has similar general features from design to final part. The first step is preparation of digital model using CAD (Computer aided design) programs [6]. In addition it is possible to use 3D scanning [7–9]. In the next step, CAD model is converted into Standard Tessellation Language (STL) file. STL file is a standard file, that contains information about 3D model [6] and it describes solely surface geometry of 3D object. This format includes splitting of surface into one or more geometric objects. For example, cube can be divided into twelve triangles [10]. Created STL file is sliced into horizontal layers. For each horizontal layer are defined printing parameters, which have significant importance of printing process [6].
In printing process, the printing head moves on X-Y plane as the tool path generated by the software and deposits the first layer onto the print bed to form a foundation for the part. When the layer is completed, the build platform moves downward for one layer thickness. Each single layer will be deposited repeatedly on previous layer until the part is completed [11]. 3D printing is automated process and issues generally only arise when machine runs out of material or when software problem occurs [12].

Depending on printing method, sometimes there is necessity to modify shape of object or to improve his mechanical properties. This process of object treatment is postprocessing [13, 14]. The basic postprocessing technique is support removal, which is characteristic of FFF method. It is based on eliminating unnecessary material waste from 3D printed part. Postprocessing consist of large number of techniques, by which we can achieve desired results [15–17].

The primary limitations of 3D printing production are connected to printable materials. The materials originally appropriate to 3D printing were thermoplastics and resins. In recent time, printing of composites, glasses, ceramics and metals is also available; this development results to large usefulness of 3D printing in various sectors of industry. Due these production opportunities, the composites become more interesting materials, because fiber reinforcements in structure can significantly enhance the mechanical properties of printed polymers [18, 19]. Although short fibre reinforced composites offer better mechanical performance than their unreinforced counterparts, there is still a substantial gap between additively manufactured composites and conventionally manufactured composites. In addition, mechanical performances determined for continuous fiber reinforced composites are better than for short fiber reinforced composites and closer to conventionally manufactured composites. Currently stereolitography and FFF are printing methods, which allow fabrication of CFRTP composites. In case of SLA, the limitations of precisely deposition of fiber are connected to resin material of matrix. FFF method is seen to be more promising method due to slight modification on print head and relatively precise mechanical deposition of fiber into structure [20–21]. Continuous fiber fabrication (CFF) represents augmented FFF process that work in addition to FFF printer to lay continuous fiber in a part. The CFF printers (for instance MarkTwo) have two nozzles; one of these nozzles deposit continuous fiber. The continuous fiber is made of various materials. Mentioned printers allow printing objects reinforced with carbon, aramid, glass or HSHT glass fiber.

2. Limitations of CFF method
Each printing method has dimension limitations of produced parts, which are defined by manufacturer and depend on printer type. For Markforged MarkTwo desktop printer, the maximum object dimensions are [22]: x = 320 mm, y = 132 mm and z = 154 mm (figure 1). In comparison to desktop printers, industrial printers allow printing of larger objects.

Minimal dimensions of 3D printed objects are also defined by Markforged: x = 1.6 mm, y = 1.6 mm and z = 0.8 mm (figure 1). Minimum part size is limited to the extrusion width and height of each bead.

The minimal dimensions are derived from the minimum number of roof layers, floor layers and shells needed to print the object successfully [22].

![Figure 1. Dimensions of printed part [22]](image-url)
Thin reinforced features must allow the fiber to double back and meet the endpoint of the fiber with its start. The minimum width of an open feature $W_{\text{open}}$ is 3.6 mm because it must fit two fiber strands. In case of part shape that allows the fiber to form a loop, the minimum width $W_{\text{looped}}$ can be at least 2.8 mm (figure 2, left) [22].

The minimum reinforceable height ($H$) is nine layers thick (figure 2, middle), leaving one layer for fiber. It means, that four roof and four floor layers are needed above and below Fiber Group. The minimum reinforceable height $H$ depends on fiber selection [22].

The smallest reinforceable area is limited to the smallest strand of fiber that can be laid down and cut. Each reinforced area, regardless its shape, must have at least 90 mm$^2$ (figure 2, right) [22].

![Figure 2. Printing limitations related to fiber deposition: minimum width of fiber reinforced feature (left), minimum height of fiber reinforced part (middle), the smallest reinforceable area (right)](image)

Other limitations are related to printing accuracy and mechanical properties of printed parts. The accuracy of the printing method is relatively low. In addition, the deposition of material results to visible layer lines, therefore postprocessing is necessary for achieving smooth surface of part. The layers are constrained using adhesion mechanism, which result to anisotropic properties of part. The success design of printed parts influences on suitable build orientation (figure 3). Material deposition makes the part weaker in one direction [23].

![Figure 3. Influence of build orientation on mechanical properties](image)

3. Modelling of CFRTP composites
Stress and deformation analysis of reinforced composites can be done at three different levels [24].

The microscopic level examines deformations and stresses at level of composite constituents [25]. Attributes, which affect results, are fiber shape, geometric distribution and properties of composite components [24].

At the macroscopic level, a composite is considered as homogeneous equivalent material, but solely deformation, buckling and vibration frequencies could be predicted [24]. Simulation at the microscopic level is limited by a computational capacity and the macroscopic level cannot calculate stress distribution in a laminate [25].
The mesoscale approach gets over these limitations and allows prediction of stresses and strains in every lamina, but elastic properties, fiber orientation and layer thickness of each lamina must be given into the program [24]. The microscopic inhomogeneity of composites linked to randomness of the fiber deposition, the bonding between fiber and matrix and the presence of microdefects causes a non-uniform response to an uniform external loading [25].

Fiber reinforced composites could be simulated using various models. In the next text a few modelling approaches will be described.

3.1. Homogenization
At the microscopic level, the composite components are randomly aligned in the structure; therefore emphasis is given on determination of overall properties. The substitution of inhomogeneous material into equivalent homogeneous material can be implemented by smearing of microscopic features at the macro level. The most widespread method is considering of periodic fiber arrays in the matrix, although real distribution of the inclusions does not correspond to periodicity arrangement [25]. This idealized arrangement of the composite structure is called representative volume elements (RVE) [26]. The purpose of the homogenization is a non-experimental determination of features of RVE material, which can be used for modelling [27]. RVE is a sample of material, which satisfies conditions, which sample structure is characteristic of the composite and it contains sufficient number of elements [28]. Applicable RVE shapes for modelling purposes of CFRTP composites are showed in figure 4.

![Figure 4. Three shape types of RVE [24].](image)

RVE represents the representative properties of the composite and allows determining influence of external loadings to behavior of the structure. The solution is based on homogenized matrices of stiffness $C^{\text{hom}}$ and compliance $S^{\text{hom}}$, which define relation between macroscopic stresses and strains [29]:

$$\langle \sigma \rangle = C^{\text{hom}} \langle \varepsilon \rangle \quad (1)$$

$$\langle \varepsilon \rangle = S^{\text{hom}} \langle \sigma \rangle \quad (2)$$

3.2. Rebar modeling
The method initially proposed [30] for modelling of reinforced concrete. The model is based on virtual work principle. The reinforcement could be modelled as smeared or discrete rebar [31].

The smeared rebars are suitable to modelling fibers in layered form, each reinforced layer has unique cross-section, material, orientation and evenly space between fibers. Each reinforced layer is assumed as homogeneous membrane having unidirectional stiffness [32].

The smeared rebar elements are represented by the element REINF 265 (figure 5), which also specifies multiple reinforcing layers [32]. These elements cannot be able to model slippage of fiber in
matrix because the rebar element is attached to the matrix elements and no relative movement between them is allowed [33]. The discrete rebar models each fiber separately. This method is appropriate to modelling of structures, which consist of sparsely deposited fibers with inconsistent attitudes, for instance fiber orientation, material, cross-section etc. The reinforcement start point and curved trajectory of the fiber in the structure do not represent complications [30], because each fiber in this method is modelled separately as beam with uniaxial stiffness. The widespread problem is bonding between fiber and matrix. Therefore representing elements, such as REINF 264 (figure 6), do not allow relative movement between composite components [34].

There are several separate cases in program ADINA, corresponding to the type of the truss element group and the type of the solid element group in which the truss elements lie [35]. There are divided into axisymetric, 2D and 3D problem. In general, the procedure of rebar element creation is equal for each problem, therefore 3D approach is described. Software generates 3D truss elements and then connects the truss elements to the 3D solid element in which 3D truss elements lie (figure 7a). Intersections between corresponding rebar line and the 3D faces are founded for each rebar line; subsequently software generates nodes at these intersections and generates truss elements that connect the successive nodes. Constraint equations are generated between the generated nodes and three closest corner nodes of the 3D element nodes (figure 7b) [35].

A few concepts of the discrete modelling suppress the bonding and allow simulation of slippage between fiber and matrix. The primary disadvantage of the method is modelling of reinforcement as one dimensional object, resulting to simulation of slippage solely in direction of fiber deposition [23].
3.3. Conformal modelling
The method based on geometry distribution of the composite model. As a result, location of the truss element representing fiber reinforcement in the structure is on edge of matrix element (figure 8). The connections between the truss elements and the solid elements are generated without constraint equations and therefore computational time consumption is reduced [36].

![Figure 8. Truss element located on edge of matrix element [36].](image)

4. Simulation of tensile testing using FEM
Standards for mechanical testing of CFRTP composite structures has not been proposed yet, therefore a simulation of the most common specimen shapes defined for tensile testing was performed with different reinforcement fiber deposition in the specimen structure. The primary aim was to observe the effect of fiber deposition on the stresses in the fibers and in the matrix.

The first assessed specimen shape was designed according to standard ASTM D3039 [37], which is specified for conventionally produced reinforced composites (figure 9a). The second specimen shape known as dog-bone was defined in ASTM D638-14 (figure 9b) [38]. This standard is given for plastics. The last specimen was a modified ASTM D638-14 specimen shape (figure 9c). The modifications of geometry were proposed in study [39] and consist of rounding at the both ends of specimen and holes for the attachment.

![Figure 9. Assessed specimen shapes.](image)

4.1. Preparation and simulation
The specimen geometry was created using the CAD program CATIA (CATIA V5, Dassault Systems, Waltham, MA) and saved as stereolithography file. The geometry in the format was subsequently
imported into Eiger. It is a slicer program – a program that converts a digital 3D model into machine-readable code for a printer (G-code). The imported model is cut into horizontal layers of defined thickness and the path of the printer head [40] is defined.

This program allows the user to set many parameters. Using Markforged's Eiger software, you can define, for instance:
- specimen deposition on the printer bed,
- type of matrix,
- fiber type,
- number of fiber reinforced layers and fiber deposition method.

The fiber deposition type can be concentric (figure 10a) and isotropic (figure 10b) – the former strengthens the edges of specimen; the latter ensures stiffness in all directions. In addition, the user can define the angle of fiber deposition in each layer.

![Figure 10. Types of fiber deposition in the structure: a) concentric, b) isotropic.](image)

In the analysis, specimen matrix consist of onyx and the specimen structure was filled with carbon fiber and different fiber deposition types, which will be described in the following text. The specimen according to ASTM D3039 was divided into 20 equally thick layers by the Eiger program. Twelve of them were reinforced with continuous carbon fiber. The fiber deposition was isotropic with three concentric fiber rings (figure 11).

![Figure 11. Fiber deposition in specimen according to ASTM D3039 [37].](image)

The second specimen shape designed in compliance with standard ASTM D638-14 was divided into twenty-six layers. The specimen was reinforced with various types of fiber deposition. Firstly, specimen reinforcement was based on the isotropic fiber fill type (figure 12a). Secondly, the specimen was reinforced with the unidirectional fiber deposition (figure 12b). Finally, the third fiber deposition type consists of three concentric fiber rings (figure 12c). The total number of fiber reinforced layers in each specimen was 18.

The last assessed specimen was divided into 32 layers. The reinforcement, which consists of three concentric fiber rings, was filled into 24 layers. In addition, two concentric fiber rings were deposited around the attachment holes (figure 13).
Figure 12. Fiber deposition in specimen according to ASTM D638-14 [39]: a) isotropic deposition and three concentric fiber rings, b) unidirectional fiber deposition, c) three concentric fiber rings.

Figure 13. Fiber deposition in specimen according to study [39].

The tensile testing of the specimens was simulated in the program ADINA using rebar elements. The fiber deposition was determined from the slicing software Eiger and the generation of models for finite element method program was performed using the program MATLAB. The fiber and matrix material model was multilinear. The generated mesh consists of 0.4 mm large quadrilateral linear elements. Mechanical properties of matrix and carbon fiber were determined from experimental measurements.

4.2 Analysis of stress distribution in CFRTP composite specimens

The stress state analysis was performed on two layers of specimen structure. The following pictures are shown in the order:

- stress in the outer layer of the matrix,
- stress in the outer reinforced layer.

The specimen designed according to ASTM D3039 is problematic in terms of attachment type. The isotropic fiber rings offers good results in case of tensile loading and three concentric fiber rings strengthens the specimen at the edges, but near to attachment occurs stress concentrations, which lead to premature failure of the specimen at improper locations. The highest stresses are approximately 16.8 MPa in the matrix and 840 MPa in the fibers (figure 14).

The specimen in compliance with ASTM D638-14 reinforced with isotropically deposited fiber and three concentric fiber rings has a maximum stress approximately 25.3 MPa in the matrix and 840 MPa in the fiber. The fiber deposition at the shoulder region of the specimen leads to generation of stress concentrations. The fiber at these locations tends to straighten under tension loading, therefore bonding between fiber and matrix disturbs which results to influence of fiber the edges of the specimen. In addition, the fiber ends located in the shoulder region affects the generation of stress concentrators, because the largest shear stress between the fiber and the matrix occurs at the ends (figure 15).
Figure 14. Stress distribution in matrix and fibers of specimen according to ASTM D3039.

Figure 15. Stress distribution in matrix and fibers of specimen according to ASTM D638-14; Specimen is reinforced with isotropic fiber fill and three concentric rings.

Secondly, the specimen according to ASTM D638-14 was reinforced with unidirectionally deposited fiber. The deposition is the most appropriate type for tensile loading. The ends of the fibers in the shoulder region also affect the occurrence of stress concentrations, therefore maximum stress approximately 25.2 MPa appear in the matrix near the region. The maximum stress in the fiber is 840 MPa (figure 16).

Figure 16. Stress distribution in specimen in compliance with ASTM D638-14 reinforced with unidirectional fiber deposition.

The last assessed specimen according to standard ASTM D638-14 was reinforced with solely three concentric fiber rings. In comparison to previous similar specimens, the lower fiber volume in structure is the case of different stress distribution, because larger part of loading is additionally transmitted by matrix. The maximum stress in the matrix approximately 20 MPa occurs at the shoulder region near the attachment of specimen. The maximum stress in the fiber is 400 MPa at the shoulder region of the specimen (figure 17).
The last assessed specimen was ASTM D638-14 with modifications. The rounding at the both ends of specimen shape suppress the occurrence of stress concentrations, but the attachment type causes the appearance of stress concentrations on the matrix (maximum stress approximately 12.6 MPa) around the holes (figure 18). Two concentric fiber rings increase the strength of the specimen around the attachment holes, but also lead to increased stresses in the matrix further to the holes. The stress concentrations at the locations results to failure of specimen at the gripping region. The maximum stress in the fibers is located at the shoulder region of the specimen and reaches a value of 218 MPa.

5. Conclusion
The results obtained from analysis and simulations allow summing of following outcomes:
• the determination of appropriate specimen shape is necessary to attain successful tensile testing,
• the fiber deposition has large influence on appearance of stress concentrations in structures, which lead to premature failure of specimen in improper locations,
• in addition, the proposal of suitable attachment of specimen and placement of fiber ends in structure are important aspects of tensile test of CFRTP composites produced by 3D printing.

The design of the specimen shape and the embedding of reinforcing fibers is the subject of further research in the field of composite materials produced by 3D printing.

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