FEM HYPOTHESIS WHICH CAN BE APPLIED FOR FDM APPLICATIONS

Mădălina-Ioana BLAJ, Gheorghe OANCEA

Department of Manufacturing Engineering, Transilvania University of Brasov, Romania (madalina.blaj@unitbv.ro, gh.oancea@unitbv.ro)

DOI: 10.19062/2247-3173.2022.23.22

Abstract: *Nowadays, with the evolution of the additive manufacturing processes and its possibility of usage for industrial applications, the tendency is to adapt, optimize or to develop new concepts for the improvement of functional parts or assemblies characteristics. One important concept is the Finite Element Method which offers the possibility to describe mathematically all the physical phenomena which occurs during the functionality of the parts. The aim of this paper is to present several hypotheses for finite element method which could be applied for the analysis of the parts manufactured through Fused Deposition Modeling, considering also the manufacturing defectives.*

Keywords: *Finite Element Method, Fused Deposition Modeling, Additive Manufacturing*

1. INTRODUCTION

From all the Additive Manufacturing (AM) processes, Fused Deposition Modeling (FDM) is one of the most used technique due to its advantages and one of the most significant demand is to anticipate the mechanical characteristics of parts, before the manufacturing process. It is well-known that the physical phenomena can be described through a mathematical model, using Finite Element Method (FEM) [1], but due to the printing parameters, materials and defectives which appear especially during manufacturing process, the FEM assumptions and theories development are challenging, the simulation results being necessary to be verified through tests in order to check the reliability of Finite Element Analysis (FEA) [2,3]. As it is presented in literature [3], the FEA results are not every time reliable to predict the future parts behavior. The researches consider the similarity with the composite materials a starting point in order to describe parts obtained through FDM method considering its structure, stiffness and strength [2].

1.1 Fused Deposition Modeling – Description

Fused Deposition Modeling is an Additive Manufacturing process which implies the creation of a specific part by adding material layer by layer, related to the part cross-section geometries. This process implies material extrusion for part formation. The main advantage of this process is the manufacturing of parts with a complex geometry and also for functional prototypes with lower costs, which is not possible to obtain through traditional manufacturing methods [2,3].

In general, materials vary from thermoplastic polymers to composite filaments and the mechanical characteristics of the final part are influenced, mainly, by the material and by printing parameters. The manufacturing parameters with the highest impact are the layer thickness and the part positioning on the building-plate.

In case of materials with chopped or continuous fibers, the porosity of the final part must be considered – the polymer is not adhering to fibers totally, causing material voids. Voids can be caused also by abnormal material deposition.

The defectives, such as material gaps, material conglomerates, non-compliant geometry or/and material rasters and fibers out of matrix which appear after manufacturing have a major impact on the mechanical properties values. For materials with chopped fibers must be considered the fact that after deposition, the fibers have a randomized orientation, the part being considered to be manufactured from an anisotropic material. It must be also considered that the part have maximized mechanical properties values on the manufacturing direction [2]. Beside of the manufacturing defectives, a part may be defined with design, assembly or service issues, affecting the conditions of usage [4]. In Fig. 1 is presented a part which has manufacturing issues – the ideal design from CAD is supposed to modification due to FDM process limitation.

FIG. 1 FDM Application – Manufacturing issues [7]

Considering the manufacturing manner, it must be considered also the thermal effect which determines the quality of the deposited material and the level of residual stresses for each part – heat transfer into the vicinity deposited material and the possibility of material slip over the already deposited material. Furthermore, it has to be mentioned the non-uniformity of part cooling, which cause morphological issues, has an increased impact over the part quality and mechanical behavior [5, 11]. Hereafter, in Fig. 2 is presented the temperature variation, considering the manner of material deposition – initially are created the edges of the cross-section in order to maintain the geometric stability and afterwards, the nozzle is passing for material deposition in order to fill the edges – the highest temperature is recorded on the latest deposited material and in its vicinity.

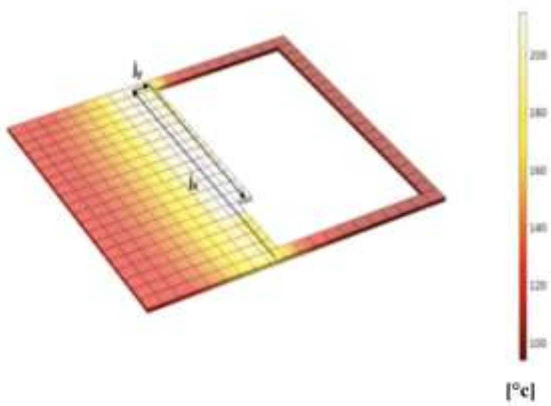

FIG. 2 FDM temperature variation [11]

Based on [2,3], the results obtained in tests are lower compared with the results presented by the filament producers – it is recommended to perform specimen tests in order to obtain the material description which can be used for FEA – issue caused by the part non-homogeneity and material anisotropy.

1.2 Finite Element Analysis – Generalities

In order to solve different engineering issues caused by structural, thermal or other physical phenomena, Finite Element Analysis is used as an analysis appliance based on Finite Element Method. FEM is a numerical technique which describes mathematically through equations physical phenomena. Hereafter in Fig. 3 is presented schematically the workflow with FEM.

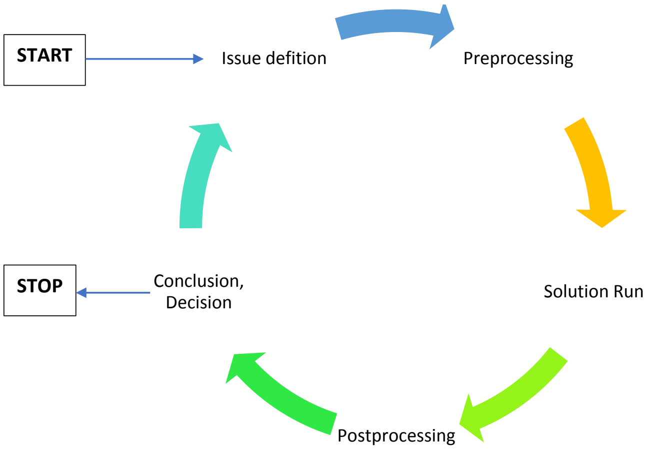

FIG. 3 FEM workflow

The result accuracy is influenced by the accuracy of the equation definitions, if they imply all the characteristics of the interested phenomena – in this case is obtained an ideal model – but considering the large amount of variables for some phenomena, the idealization is not possible every time, the results being obtained based on assumptions. The results represent the behavior of the engineering system which must be analyzed, which is not accurate in all cases.

Considering all the steps for a FEA, in each step can be applied assumptions with a different level of impact over the final results, causing inaccuracies and impossibility of usage. Mainly, these steps are referring to: modeling/meshing, material definition, loads definition, boundary condition definition and the analysis solution [1, 3].

1.3 Filament description for FEM Applications

The material resulted after manufacturing is anisotropic, with many similarities to composite materials – it has different properties in all directions of a random material block which is defined in Figure 4 [12, 15]

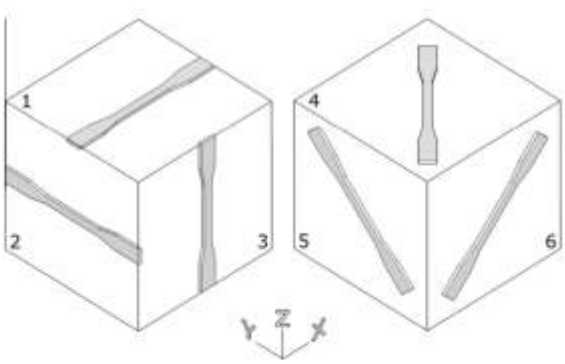

FIG. 4 Material specimen definition and extraction in 6 directions [15]

According to developed research by different authors [2, 10, 15], the material used for FDM applications is defined as an orthotropic material with a linear behavior, as an assumption and to reduce the mathematical system from 36 components – for anisotropic material, which are defining the relation between stress and strains considering Hooke's Law into a linear elastic regime. Based on this assumption – the material has 3 mutually perpendicular planes of symmetry, the new reduced mathematical system has 9 components.

2. FEA APPLICABILITY FOR FDM APPLICATIONS

The researches have a different approach for FEA in case of FDM parts, considering much or less the entire description of the phenomena which appear during manufacturing and also in usage, under the influence of certain loads and external environment. In the Table 1 is presented a literature review of methods and assumptions used for FEA of FDM applications, for the first 2 steps which has an increased impact over the results.

Table 1. Literature review – FEA Assumptions for FDM applications

Ref.	Modeling/ meshing	Material definition	Remarks
[3]	CAD fidelity with the printed part, HEX6 elements	Isotropic, orthotropic, laminar material approach	Analysis not able to predict the crack area, large deviations from tests
[6]	Modelled gaps, fine mesh	Isotropic material (PLA)	Stress concentrators near gaps Laminar material approach to be done
[9]	Shell elements	Orthotropic approach	No validation with experimental data
[10]	2 models: as a solid & as a stack with laminae	Orthotropic & laminar approach	Delamination can be identified for laminar approach No validation with experimental data
[13]	Solid & Temperature considered	Orthotropic approach	Comparison with experimental tests
[14]	Shell elements	Each component with its properties	Comparison with experimental tests
[15]	Solid	Isotropic	The anisotropy must be defined

As it is stated in [3], in order to obtain a feasible FEA, it is important to understand the FDM process and its each parameter influence over the mechanical properties. As a conclusion from Table 1, it must be mentioned that there is no ideal model or method to perform a FEA for a FDM part, in this case validation tests being a must.

In order to obtain a closer design to the final part, in a research [3] is used the G-Code to recreate the ideal design from CAD Model. Due to the fact that the G-Code has layer intersections and/or overlaps, the geometry is supposed to be checked and "cleaned" by interferences in order to have the possibility to create the part meshing. The disadvantage of this method is the high time for processing and running. In order to use lower resources, another approach is to use a continuous model and if there any infill is used, this should be modelled on its position.

As there can be different methods of material modelling, the most reliable approach is to model material as an orthotropic one, but still in this manner, the results do not have the expected accuracies [3]. The orthotropic material modeling takes in consideration the material anisotropy of the FDM part.

For a proper accuracy, in another study [7] is modelled the part in Additive3D by Abaqus with the temperature history during and after the deposition process, considering also the residual stresses and warpage of the part based on the material crystallization phases. The heat transfer can be simulated also with MatEx, taking in consideration the fact that real-time temperature measurements are difficult to be performed due to its limitation of measurement on the surface or near the surface [8]. It must be mentioned that no temperature influence is considered for calculation [3, 6, 9,10].

In the literature [10] it is highlighted the realistic behavior of the layer-by-layer model, in this manner existing the possibility of identification of other failure modes, such as delamination – it is not possible to identify for solid models.

3. FEM HYPOTHESIS FOR FDM APPLICATIONS

Considering the literature review above presented, it can be summed up that any method obtained not so accurate results, in each research being used some specific assumptions, with a different level of impact. Discussing also about the study from [2], the phenomena which appears during FDM process must be defined in FEM as much as possible, considering the time and computational resources limitations.

The majority of the researchers used an orthotropic approach of the material or a laminar approach – both methods are reliable and can be developed considering also a detailed modelling [3], but also considering the temperature effect and the manufacturing defectives.

Detailed modelling can be performed into an automatic manner [1], considering the G code obtained for slicing, the intersections and overlaps between geometry being mandatory to be corrected in order to create the mesh. For meshing, more detailed information solid elements are chosen. The element size must be adapted also by computational resources, but a fine mesh should be used, reported to the layer thickness.

One first approach is to perform an analysis considering a solid model with a similar geometry as the printed part, but also with temperature effect applied. Another approach is to perform an analysis with the assumptions mentioned above, but with material defined in lamina, with a specific material orientation – in order to obtain information about other failure modes which are identified in experimental test. Due to the similarity with composite materials, another approach is to consider the model to be made from a composite material, where the properties for each component must be defined – in case of usage of filament with fibers.

After post-processing, the obtained data should be compared with experimental results, in order to validate the tests.

CONCLUSIONS

For researchers the applicability of FEA is a challenge due to its many variables which interfere into the model definition in FEM environment. As long as too many assumptions are make and with a certain impact, the results of analysis are going to be not so accurate.

As long as many researches consider modeling in detail the resulted part after manufacturing a difficult process, a possibility of time and work load reduction is to automatize and to use the G Code for the part which is going to be analyzed. Another important topic is regarding the material definition, which can be considered as an orthotropic material in order to obtain as much as possible the realistic behavior. In order to validate the hypothesis used, it is recommended to perform experimental tests.

REFERENCES

[1] M.I. Blaj, G. Oancea, Parametric design of a complex part in a FEM environment, *MATEC Web of Conferences*, vol. 299, art. no. 3005, 2019;

[2] M.I. Blaj, S.M. Zaharia, M.A. Pop, G. Oancea, Tensile Properties and Manufacturing Defectives of Short Carbon Fiber Specimens Made with the FDM Process, *Materiale Plastice*, vol. 59, no. 1, pp. 33-43, 2022;

[3] P. Baikerikar, C. J. Turner, Comparison of FEA simulations and experimental results for as-built additively manufactured dogbone specimens, *The International Journal of Advanced Manufacturing Technology*, vol. 115, pp. 2839-2851, 2021;

[4] D. H. Stamatis, *Failure Mode and Effect Analysis FMEA from Theory to Execution*, Milwaukee, Wisconsin, ASQ Quality Press, 2nd ed., 2003;

[5] J. Kattinger, T. Ebinger, R. Kurz, C. Bonten, Numerical simulation of the complex flow during material extrusion in fused filament fabrication, *Additive Manufacturing*, vol. 49, art.no. 102476, 2022;

[6] A. Alafaghani, A. Qattawi, B. Alrawi, A. Guzman, Experimental Optimization of Fused Deposition Modelling Processing Parameters: a Design-for Manufacturing Approach, *Procedia Manufacturing*, vol. 10, pp. 791-803, 2017;

[7] B. Brenken, E. Barocio, A. Favaloro, V. Kunc, R. B. Pipes, Development and validation of extrusion deposition additive manufacturing process simulations, *Additive Manufacturing*, vol. 25, pp. 218-226, 2019;

[8] A. D'Amico, A.M Peterson, An adaptable FEA simulation of material extrusion additive manufacturing heat transfer in 3D, *Additive Manufacturing*, vol. 21, pp. 422-430, 2018;

[9] D. Jungivala, P. K. Gurrala, Finite element analysis of fused filament extrusion build part using different build orientation, *Material Today: Proceedings*, vol. 38, pp. 3264-3268, 2021;

[10] j. Martinez, J.L. Dieguez, E. Ares, A. Pereira, P. Hernandez, J.A. Perez, Comparative between FEM models for FDM parts and their approach to a real mechanical behaviour, *Procedia Engineering*, vol. 63, pp. 878-884, 2013;

[11] A.A. Samy, A. Golbang, E. Harkin-Jones, E. Archer, D. Tormey, A. McIlhagger, Finite element analysis of residual stress and warpage in a 3D printed semi-crystalline polymer: Effect of ambient temperature and nozzle speed, *Journal of Manufacturing Processes*, vol. 70, pp. 389-399, 2021;

[12] M. E. Tuttle, *Structural Analysis of POLYMERIC Composite Materials*, CRC Press, 2nd ed., 2013;

[13] S. Hasanov, A. Gupta, A. Nasirov, I. Fidan, Mechanical characterization of functionally graded materials produced by fused filament fabrication process, *Journal of Manufacturing Processes*, vol. 58, pp. 923-935, 2020;

[14] N. van de Werken, J. Hurley, P. Khanbolouki, A. N. Sarvestani, A. Y. Tamijani, M. Tehrani, Design considerations and modeling of fiber reinforced 3D printed parts, *Composites Part B*, vol. 160, pp. 684-692, 2019;

[15] M. Domingo-Espin, J. M. Puigoriol-Forcada, A.A. Garcia-Granada, J. Lluma, S. Borros, G. Reyes, Mechanical property characterization and simulation of fused deposition modeling Polycarbonate parts, *Materials & Design*, vol. 83, pp. 670-677, 2015.