Prediction of Printing Failure of a 3D Printed Drone Propeller using Fused Deposition Modeling

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Abstract: *Fused Deposition Modeling (FDM) is a 3D printing process where thermoplastic materials are deposited layer by layer through an extrusion nozzle. One of the main advantages of an FDM process is that any complex shape geometry can be printed directly from a CAD model. However, the process also shows disadvantages such as air-gap, porosity, weak inter-layer bonding due to thermal gradient, which lead to unwanted print failure at the time out of the machine or under in-service conditions. Therefore, it would be beneficial to model and predict possible print failures early at part and process design stages in order to reduce the scrap rate and decrease product development cycle.*

In this paper, a drone propeller is used as an example to illustrate the print failure modeling strategy. The commercial finite element software package ABAQUS is used to simulate the FDM printing process and in-service performance of the propeller. In order to analyze the printing process, a heat transfer analysis is done first to predict the temperature history of the part, which drives the stress analysis for distortion and residual stress predictions. The tool path patterns dictate how material is added during the printing and it also have direct influence in the residual stresses in the part. Abaqus uses machine tool path as a direct input and solves the local orthotropic material properties and evolving cooling surfaces using the event series and progressive element activation technologies. With residual stresses and strains mapped from virtual printing simulation, in-service loading is also applied to predict the high stresses and displacements zone, which have higher possibility of failure. The results of the in-service condition of a 3D printed propeller is compared with a non-3D printed propeller, having same material properties and dimensions and in-service conditions. The comparison clearly shows that the 3D printed propeller has more stress all over the propeller body than the non-3D printed one, which make them more prone to breakage.

Keywords: *Additive Manufacturing, 3D Printing Process, Process Simulation, Heat Transfer, Residual stresses, Drone Propeller, In-service performance, Distortions*

1. Introduction

Additive manufacturing (AM) is a great inventions of modern era, which has introduced a great step in the manufacturing of consumer goods [Brischetto et al, 2017]. And being cheap & easy to use, FDM has become one of the most common AM processes. In FDM process the 3D printer receives filaments from a coil and melts that filament above its glass transition temperature and deposits it in a layer by layer bottom-up manner using a nozzle to build the desired shape. The filaments are production grade thermoplastics, which are mechanically & environmentally stable. AM helps to manufacture complex shape geometry and cavities very rapidly which were previously very problematic to produce [stratasys]. The usage of this technology is expanding exponentially from manufacturing prototypes to small series of specialized parts in many application area [Koch et al, 2017] and among them Drone Technology is one of the most impacted area.

Drones are a kind of aircraft that can fly autonomously or can be remote controlled. In past few years, with the advancement of technology, the market of drones are growing rapidly. Now it's being used from package delivering, monitoring to farming [Ferro et al, 2016]. Recently, companies like Amazon, Walmart are using small drones to deliver their products to customer within minutes, previously which was time consuming & costly [Montgomery, 2017]. But manufacturing of these useful drones are expensive, laborious and due to its weight it is constrained by operational range & flight time [Ferro et al, 2016]. Recently many researches have been conducted using AM to reduce the structure weight, to maximize flight time & range [Ferro et al, 2016], to easily produce adjustable arms for specific purpose [Brischetto et al, 2016] and to construct the drone in a fast & economic way [Brischetto et al, 2017]. However, one of the most important factors is the drone propeller, as it directly influence the aircraft's performance and impact the propulsion system [Rutkay, 2014]. On the other-hand, propeller of these small drones are very prone to breakage during operation as it frequently gets hit by bushes and small trees. Sometimes these small drones doesn't have the landing gear, it requires belly landing or striking a net, which frequently damage the propellers [Rutkay, 2014]. Therefore it is often needed to replace the propeller, and a 3D printed propeller is the most suitable, fast and economical replacements. And the suitability of 3D printing for manufacturing flight-worthy propellers has been investigated and found reliable [Rutkay, 2014].

In a 3D printed propeller there is a chance of having high thermal stresses & voids among adjacent filaments around the curvature shape body, at the blade root or at the trailing edges [Coogan et al, 2017, Rutkay, 2014], which leads to interlayer weak bonding & delamination from that particular layer. Again if the material possess high thermal expansion property the part can be damaged during printing [Kujawa, 2017]. These factors greatly influence the mechanical behavior & lifespan of the 3D printed propeller. Therefore prediction of these factors prior to printing will have a positive impact on the improvement of interlayer bonding, overall strength, usage and long term performance of the propeller. The work here presented, predicts the high stress zone of a 3D printed drone propeller at process design stage and compare the stresses developed during in-service conditions between a 3D printed and non-3D printed propeller, both of which have the same material property and in-service conditions. ABAQUS is used to simulate the 3D printing process virtually which provides stresses as output. ABAQUS is also used to apply the in-service loadings [Rutkay, 2014] in a rotating frame condition for both 3D & non-3D printed propeller to get the stress and displacement zones of them.

2. Methodology

2.1 3D printing Process

The Additive Manufacturing Framework (AMF) in ABAQUS is used to conduct the simulation for 3D printing process. The AMF is a newly developed framework to provide accurate and scalable predictions of Additive Manufacturing printing process. This framework has wide range of features to perform the 3D printing process like it accepts varying finite element mesh density and input of process parameters, can handle different process specifications like bead area of deposited layers, moving speeds, layer direction etc, can also handle the intersection between tool-path and finite element mesh to progressively activate, either partial or full, the elements. The AMF is capable of computing transient heating and cooling of the progressively activated element during the activation and can analyze customized output from the process simulation. In this section a simple cube model is used to describe the FDM process simulation using the Additive Manufacturing Framework.

The detailed tool-path of the cube CAD model, generated from SOLIDWORKS, was provided by Stratasys. The tool-path file contains the moving speed of the nozzle, specific nozzle co-ordinates related to specific time and bead widths. This tool-path data can be extracted in different readable formats. A python script was generated to convert the tool-path as Event-Series for ABAQUS analysis. This event series file contains all the necessary information from the tool-path file including time, spatial position of the nozzle head and deposition bead specification. An ABAQUS plugin AM Modeler is used to visualize the tool-path as shown in Figure 1. An input file for the cube model is generated where all the mesh details and materials properties are included. The event series is inserted into the cube input file as an input data. The tool path co-ordinates lies within the cube body and intersects with all the associated elements as shown in the Figure 2. The too-path always follow a linear path and moves from the starting position to next. The bead width and height are used to make a rectangular box which moves with the tool-path keeping the linear path at its center. Figure 3 shows the linear red line of the tool-path is at the middle of the boxes and describes how the rectangular boxes follow them. During the tool-path movement along with the rectangular box the element activation occurs. The element activation completes in two steps and is independent of mesh density and element type & size. At first, a predefined search radius in the event series search for any adjacent elements from the whole event series keeping the linear path at its center, and then search if those elements are within its search radius. All the elements and element properties within the search radius get activated. The AMF is also capable of customized partial element activation. In this case, only half, either above or below, of the element gets activated along with the tool-path and the other half activates when the next layer is deposited. It is very suitable for varying deposition bead event series and curve shape geometry. The Figure 4 below shows the progressive element activation along the tool path.

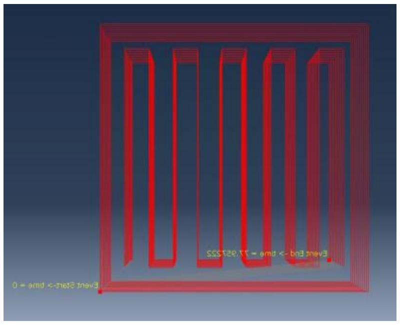

Figure 1. Tool-path for the Cube model

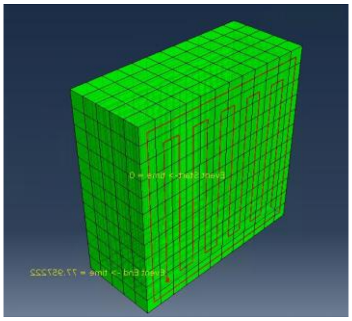

Figure 2 Tool-path within the element

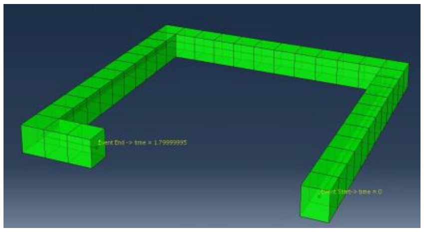

Figure 3. Tool-path position within an element

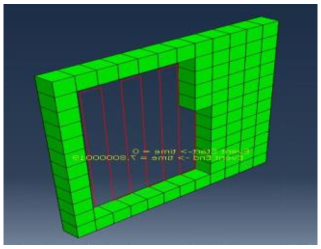

Figure 4. Element Activation following tool-path

Materials are treated as orthotropic in this analysis and material orientation along with the tool-path are assigned using an available ABAQUS user subroutine ORIENT. Another ABAQUS customizable input deck framework named “Table Collection” is assigned to control the event series, stack direction, bead height & width and the element activation. In this paper, similar 3D printing process simulation is done on a complex shape geometry, drone propeller, to predict stresses developed right after the 3D printing and then in-service loading is also applied on it to identify whether the 3D printed propeller produces more stress than the non-3D printed one.

2.2 In-service Conditions for a propeller

To simulate the in-service performance of a propeller one can use CFD analysis in a stationary frame or static analysis in a rotating referenced frame. Delapierre et al, 2016 found that accurate results can be achieved more quickly using a rotating referenced frame. In this paper, rotating referenced frame is used to do conduct the in-service performance simulation. For a rotating referenced frame one need to consider three fictitious force-

Centrifugal force, $F_{cen} = -\rho\Omega * \Omega * r$ Equation 1

Rotary acceleration, $F_{Euler} = -\rho\left(\frac{d\Omega}{dt}\right) * r$ Equation 2

Coriolis force, $F_C = -2\rho\Omega * V_r$ Equation 3

Where $\Omega(t)$ is the angular velocity, V_r is the velocity in the rotating frame, ρ is the density of the material, r is the distance from the center.

All of these forces are readily available in ABAQUS library. For the analysis of the propeller, the angular velocity is considered as constant and the value is taken as 3500 rpm from THESIS. Therefore, the rotary acceleration becomes zero. And the other two forces are directly uses from ABAQUS CAE module for non-3D printing analysis and ABAQUS user subroutine *DLOAD is used for 3D printing analysis. The input parameters for those loadings are followed from the ABAQUS 2018 documentation.

3. Finite Element Simulation

3.1 FE Simulation for non-3D printed propeller

The non-3D printed propeller is considered as a propeller which is made from other manufacturing processes like injection molding process. In this paper, a propeller with a definite shape, dimension and size is used for both 3D printed and non-3D printed analysis. The production grade thermoplastic material ABSplus-P430 is used as the propeller material and the properties are given in Table 1.

Table 1. Material property of ABAplus-P430

Tensile Modulus (MPa)	**Poisson's Ratio**	**Density (kg/m3)**	**Conductivity (W/mK)**	**Coefficient of Thermal Expansion (µm/mK)**	**Specific Heat (J/kgK)**
2200	0.35	1040	0.19	80	1620

Due to the curvature shape body of the propeller, ABAQUS cell partition feature is used to achieve a uniform meshing all over the body. To obtain better result tetrahedral meshing having C3D10 element type is used. The Figure 6 shows the detail view of the meshing. In-service loading conditions [Rutkay, 2014] is applied all over the propeller body to get the stress & distortions developed during the performance.

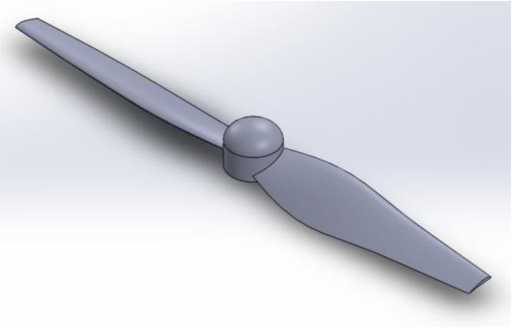

Figure 5. CAD model of the propeller

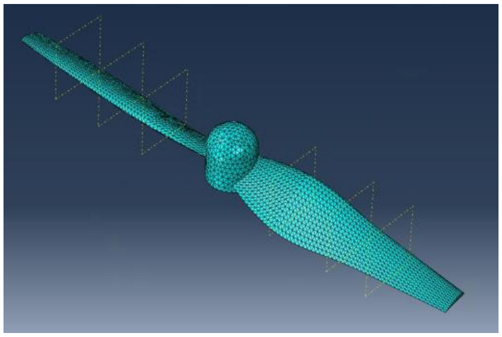

Figure 6. Mesh details of the propeller

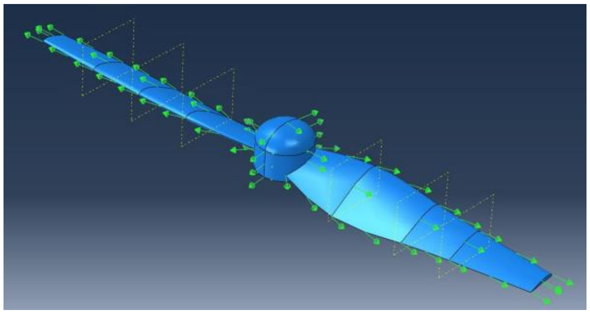

Figure 7. Loadings on the propeller

FE Simulation for 3D printed propeller: The drone propeller is a very complex shape geometry, Figure 5, and due to its curvature shape body event series with varying bead cross section area are required to capture the printing process more accurately. As a result, multiple event series is used to complete the whole printing process. The same ABSplus-P430 material is used for the 3D printing analysis. To compare the result and better progressive element activation same meshing is used as the non-3D printing propeller. All of these node and mesh details are documented into an input file to conduct the 3D printing process simulation. The detail view of the propeller tool-path is shown in Figure 8. Partial element activation is used for this analysis and the element activation follows the same procedure as discussed earlier. The Figure 9&10 shows how the elements are activating during the 3D printing process simulation of the propeller.

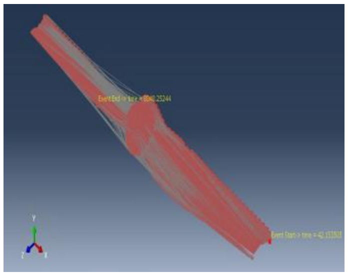

Figure 8. Tool-path of the propeller

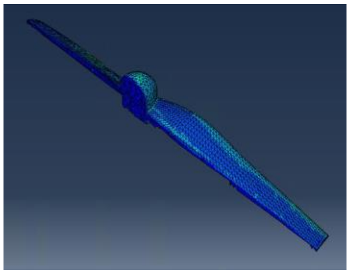

Figure 9. 50% Elements got Activated

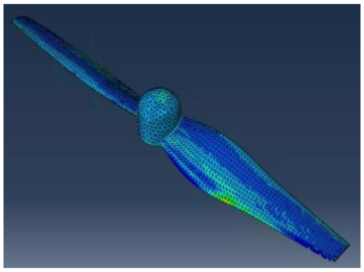

Figure10. All elements activated

A sequentially coupled thermal-mechanical process is conducted to predict the residual stress value in an as-manufactured 3D printed propeller. In this process, a heat transfer analysis is done first to obtain the time dependent temperature history of the deposited filaments. Taking this heat transfer result as an input, static analysis is conducted to do the residual stress and part distortion calculations. After the completion of the 3D printing process for the propeller, all the residual stresses and distortions results are mapped into another subsequent *STEP to perform the in-service analysis for this printed propeller.

4. Results and Discussion

The main focus of the paper is to compare whether there is any significance difference in terms of stress and distortions between a 3D printed drone propeller and a non-3D printed propeller when they are in in-service conditions. The results are shown and discussed in the following section.

4.1 In-service simulation results for non-3D printed propeller

The finite element simulation for the in-service condition of the non-3D printed propeller is conducted using ABAQUS CAE. After the meshing, loadings are applied on the propeller body as discussed in the methodology. Since rotational frame is used for the analysis, pinned boundary condition is applied at the bottom edge of propeller hub. The results of stresses developed from the in-service simulation is shown in figure 11. From the figure 11 it is clear that high stresses about 1.45 MPa are developed around the propeller root, which was expected. At the mid-span the stresses goes down to 0.8 MPa and becomes very less which is 0.2 MPa at the propeller tip. These stresses distributions were expected because the propeller hub is attached with a shaft and the propeller blade is rotating freely with high rotational speed and centrifugal force. The distortions output on the propeller body due to the loadings are shown in figure 12. The distortions at the propeller root is zero (0) because the propeller blade is attached with the hub. The propeller tip have the high displacement which is 0.02 mm. In the figure the displacements looks very large because large deformation scaling factor is used to show the displacements clearly.

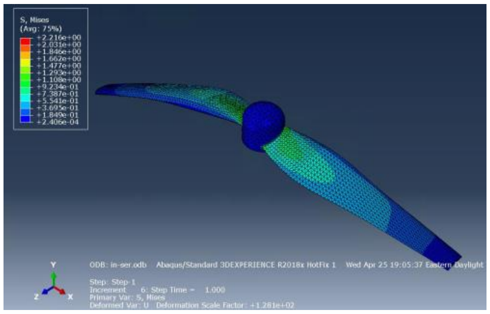

Figure 11. Stresses output

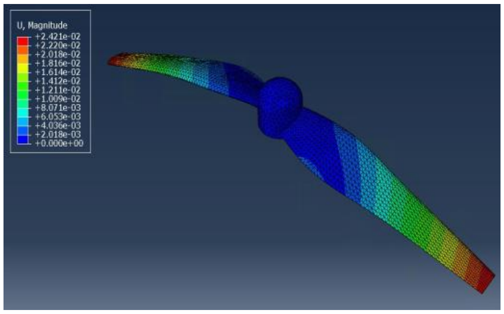

Figure 12. Distortions output

4.2 Printing Process and in-service performance results for 3D printed propeller

4.2.1 Stresses & Distortions developed after the 3D printing

The finite element simulation for both the printing process and in-service conditions is conducted using ABAQUS Additive Manufacturing Framework. The process simulation for the 3D printed propeller is done by the same procedure discussed earlier. The process simulation is done in two steps. At the first step heat transfer analysis is done. The nodal temperatures after the completion of 3D printing is shown in figure 13. The temperature of almost all the previous layers has cooled down. However, the temperature at the left most of the propeller is a bit higher than the others because this is the last layer deposited and still need some time to cool down to the minimum temperature. This heat transfer result is used to drive the residual stress & distortion analysis due to 3D printing of the propeller.

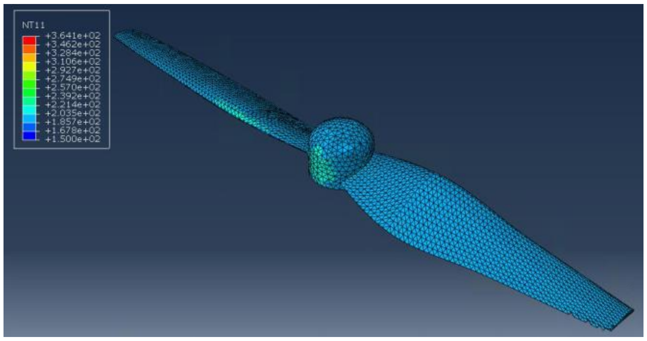

Figure 13. Nodal temperatures after 3D printing

Figure 14 & 15 shows the residual stresses and distortions developed due to the 3D printing. The stress value right after the 3D printing is shown in figure 14. The stresses at the leading and trailing edge is very high, around 1.5MPa. This is because these edges have very sharp geometry and due to the layer by layer deposition of 3D printing any sharp geometry is very difficult to print accurately which introduces larger stresses at those region. Again during 3D printing due to high thermal gradient between the previous layer and the newly deposited layer, there always developed a high residual stresses. And due to this high residual stresses after the 3D printing the printed body distorts a little bit. For the propeller the distortion is 1.5mm at the propeller tip. The propeller tips distorted more because this portion was above the build platform, though there was support material at the edge but these support materials also distorts at the same time due to high thermal gradient.

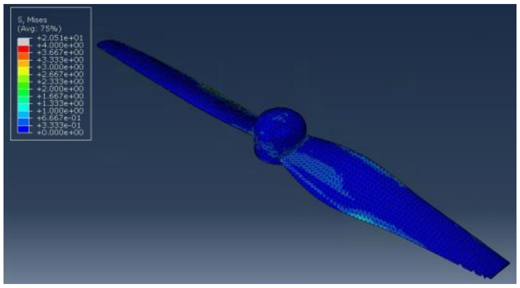

Figure 14. Residual stress output after 3D printing

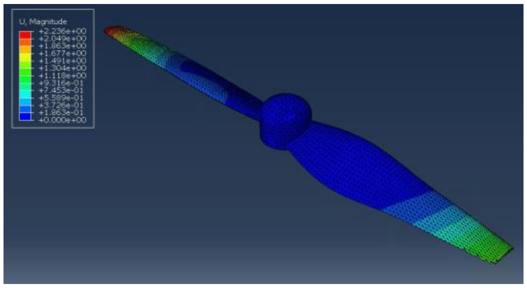

Figure15. Distortion output after 3D printing

4.2.2 Stresses & Distortions developed after the in-service performance

From the Figure 16 it is clearly seen that the stresses around the propeller trailing edge is very high and is around 11MPa as this region possesses very sharp edge. The stresses at the propeller root is around 3.5 MPa which also high very high with respect to the in-service conditions of non-3D printed propeller. At one trailing edge the stresses goes very high value. This is because of the fixed boundary condition at that edge. This issue will be fixed in the final submission. The figure 17 shows the distortions after the in-service conditions of the 3D printed propeller. There is no distortions at the propeller root but at the propeller tip the distortions are very high which has an average value of 20mm. This high distortions is the result of very high stress at the propeller mid-span. Due to this high stress at the mid-span and high centrifugal force on the propeller blade, the mid-span started to bend which results in high displacements at the propeller tip.

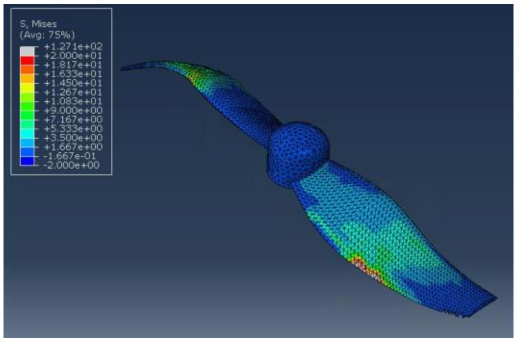

Figure 16. Stress output after in-service loadings

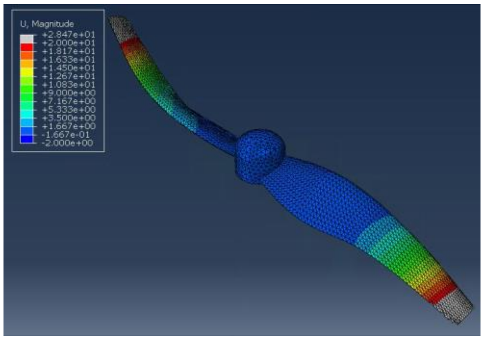

Figure 17. Distortion output after in-service loadings

5. Conclusion

The comparison of results between the non-3D printed and 3D printed propeller shows a very interesting and obvious results. The comparison of in-service conditions between figure 11 & 16 for stresses and figure 12 & 17 for distortions dictates that the 3D printed propeller produces much more stresses and distortions than the regular non-3D printed propeller which makes the 3D printed propeller more prone to breakage during the performance. The breakage or damage of a drone propeller increase the chance of losing the drone as well as reduce its performance, so buying a new propeller every time is not economic. On the rather hand, making of a 3D printed propeller is very easy, fast and economic for anyone. And also the reliability of performance of a 3D printed propeller is tested by David Rutkey, 2014. So, using of 3D printed drone propeller will be beneficial in all aspects instead of using the traditionally manufactured propeller.

6. Future Work

The work presented here motivates the study of printing and in-service failure of a complex shape geometry like the propeller. The ABAQUS Additive Manufacturing Framework can predict all the temperature history, high stress zone and distortions. These results will be mapped to conduct the study of failure. Cohesive surfaces can be applied at those high stress zones to verify whether the stresses developed during the printing process and in-service conditions reduced. Modeling of printing failure and in-service conditions will also be very helpful to improve the print quality, strength and reliability.

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