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Technical Paper

Evaluation of the influence of build and print orientations of unmanned aerial vehicle parts fabricated using fused deposition modeling process

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ABSTRACT

The principal objective of this study is to provide an insight into the simulation of fused deposition modeling (FDM) parts considering the influence of build and print orientations. The elastic modulus, strength and Poisson's ratio at different build and print orientations are obtained by performing uniaxial tensile tests. Based on the results, an appropriate material model is formed and validated by conducting flexural tests on a flat and curved layer FDM (CLFDM) parts fabricated in various print and build orientations. It is found that the influence of the print orientation or different raster angle is minimal and an averaged isotropic material model can be used to simulate parts in a particular build orientation. The build orientation influences the elastic mechanical response of the flat and CLFDM parts largely. A case study on a flying wing unmanned aerial vehicle (FW-UAV) is presented to analyze the contribution of the build orientation on the strength of the structure. The case study shows that the effect of build orientation in some instances might not be critical and a thorough understanding of the loads interacting with the part is necessary before analyzing the building parameters.

1. Introduction

The build and print orientations are essential printing parameters while fabricating functional end-use parts using the fused deposition modeling process (FDM). The FDM technology manufactures parts by extruding semi-molten thermoplastic materials and arranges them in layers. The variation of the manufacturing orientations within the printer volume results in variations in the microstructural design, thus affecting the mechanical behavior of the printed components [1,2].

Several researchers have studied the effect of print [3–7] and build orientations [8–11] on the mechanical capability of FDM parts. Invariably, the researchers conclude that these printing parameters induce anisotropy in the mechanical response on a varying scale depending on the printer type and materials used. Although these results provide an insight into the selection of appropriate printing orientations, it is vital to quantify the difference in stiffness and strength occurring due to different printing orientations, especially for simulating these parts in the pre-design phase. Also, an analysis on the influence of build and print orientations on the mechanical performance of the part is necessary since there are certain advantages of printing in a particular direction. One such example is the ability to print tall structures when the part is oriented in a way that the layers are stacked one above the other. Building in this orientation might be critical in the fabrication of unmanned aerial vehicle (UAV) parts, especially wing sections, since it is structurally beneficial to reduce the number of joints in a component. Hence, it is important for a designer to simulate FDM printed parts to check their mechanical response to an applied load before making plans for 3D printing.

Simulating FDM printed parts using the finite element (FE) method requires a material model which must be robust; and the method adopted in deriving this model has to consider the effect of print and build orientations. In [12], the FE method is implemented to compare isotropic and anisotropic material models to simulate FDM parts and is concluded that an FDM part must be considered anisotropic. The article that aligns closely to the contributions of this paper is [13], where an orthotropic material model for computing the stiffness matrix to simulate FDM printed polycarbonate parts at various build orientations. It concludes that an isotropic material model is sufficient to simulate FDM parts with different build orientations. The mean values of the elastic mechanical properties in different build directions are given as an input to the FE solver. In addition to the work presented in the aforementioned article, the research in this paper also focusses on

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investigating the effect of varying raster angles or the print orientations while simulating an FDM printed part. Another closely related study is conducted in [14,15] on acrylonitrile butadiene styrene (ABS) and ULTEM parts respectively. The article concludes that the arrangement of the layers or the build orientation to the direction of the application of load is critical to the mechanical response of an FDM printed part.

The motivation of this research article arises from the inquisitiveness to analyze the capability of FDM as a manufacturing technology to fabricate UAV components. To reduce the lead time of the UAV, the parts are often arranged or stacked in different directions to maximise the usage of the print volume. In such cases, the build and print orientations of various parts are different, and the designer needs to include their effects in the computational environment to analyze the performance of the component accurately. In this paper, the effects of both print and build orientations on forming an appropriate material model for simulating FDM printed parts are presented. The elastic mechanical properties are obtained through the uniaxial tensile tests. Based on the results of the uniaxial tensile tests, certain assumptions are drawn and validated by conducting simulation on the representative parts. Finally, a strength-based design analysis on a flying wing UAV (FW-UAV) is presented to analyze the criticality of build and print orientations in the fabrication of the structure through the FDM process.

The article comprises of three sections. In Section 2, mechanical characterization of FDM printed parts and the influence of print and build orientations on them is discussed. Also, a valid material model is formulated and validated through the experimental and numerical investigation on flexural tests on flat and CLFDM parts. Section 3 applies the assumptions made for finalising the material model to the FW-UAV structure to determine the contribution of part orientation to the strength of the structure. Taguchi and ANOVA analyses are conducted to accomplish the same and vital conclusions are drawn in Section 4 for simulating FDM printed UAV parts at various print and build orientations.

2. Experimental and numerical procedures

The experimental and numerical procedures conducted in this article can be divided into the following parts:

1. *Uniaxial tensile tests-experimentation and results:* Mechanical characterization of the FDM parts is accomplished by manufacturing them in different build (edge-up (EU),face-up (FU) and straight-up (SU)) and print orientations (0–90°) as shown in Fig. 1. Morphology of the fractured surface is obtained by using scanning electron (SEM) and optical microscopes. The images are studied to understand the influence of print orientation to the elastic modulus and strength of the specimen. The Young's modulus and the ultimate tensile strength of FDM parts in different build and print orientations are presented and a suitable material model is predicted accounting for the changes in build and print orientations.
2. *Testing of representative samples:* The flexural behavior of flat and curved layer FDM (CLFDM) samples in different build and print orientations is shown. Since the slicing software used for the printer has different travel/toolpath algorithms for flat and curved samples, an additional analysis should be conducted for the curved parts [16–18]. Geometrical aberrations arising due to the build orientation of a CLFDM sample is analyzed to ensure their influence on the physical response is not profound.
3. *FE simulation of the representative parts:* FE analysis of the flat and CLFDM samples are conducted using the commercial FE package, ABAQUS, and the material model predicted in the previous section is validated.

All parts in this article are fabricated using the Stratasys Dimension Elite FDM printer which has a print volume of 203 × 203 × 305 mm. ABS*plus* is the model material and a polymethyl methacrylate based

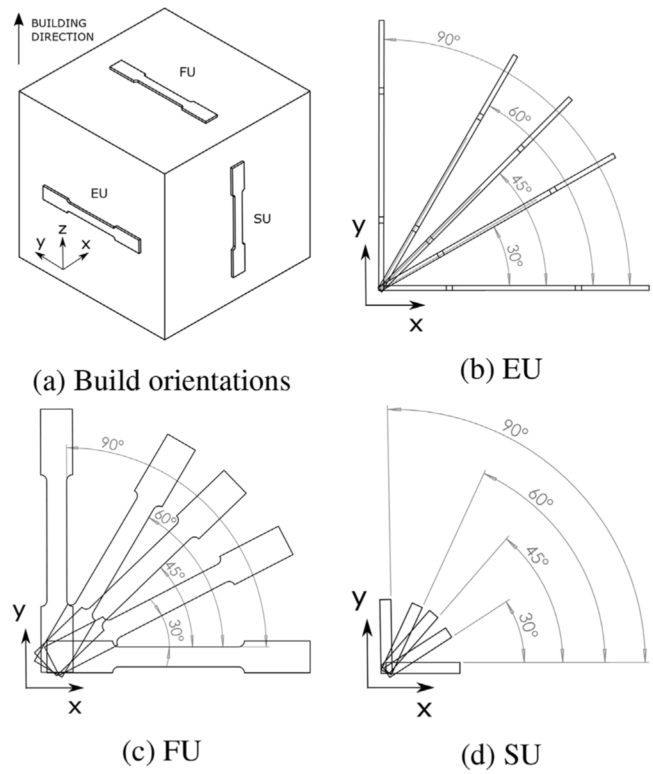

Fig. 1. Tensile specimen oriented in various build and print orientations.

support material, P400SR, which is soluble in alkaline water is used as the support. The parts are fabricated with a layer thickness of 0.1778 mm and orients it at +45°/−45° to obtain parts with enhanced complex load bearing capability [19]. STL files of the samples are generated using Solidworks® 2015 CAD package.

2.1. Uniaxial tensile test: experimentation and results

The tensile test samples are prepared according to the ASTM D638-10 Type-1 standard [20]. Five sample are printed for each build and print orientation, amounting to a total of 75 samples. Shimadzu AGX-*plus* desktop testing machine with a load cell capacity of 10 kN is used for performing the tensile tests. The testing system is fitted with TRViewX optical extensometer capable of capturing the axial extension and width in the gauge region of the sample. The tests are performed at a constant displacement rate of 5 mm/min. Fig. 2 presents the stress-strain trends for FDM printed uniaxial tensile test samples printed in

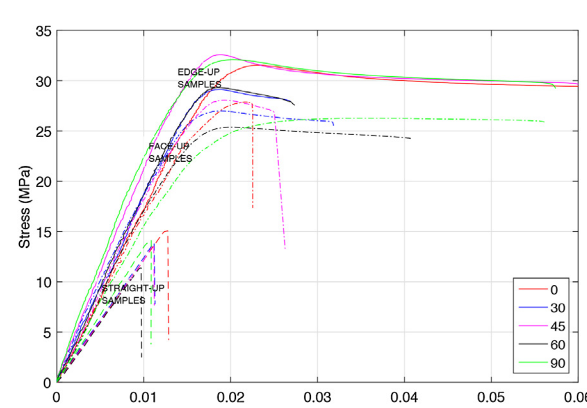

Fig. 2. Representative stress–strain plot for flat samples at various print and build orientations.