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Analytical and Numerical Assessment for the Modeling of Multi-Material Structures

Tirukovalluru venu Kumar, Dr. G. Kalivarathan
Research scholar, Dept of Mechanical Engineering , CMJ University.
Supervisor, Dept of Mechanical Engineering CMJ University

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ABSTRACT
The technology known as Additive Manufacturing (AM) is evolving quickly and is being incorporated into both manufacturing and daily life. The concept behind additive manufacturing (AM) is that it is a process that enables 3D designs to be produced directly from computer-aided design files without the need for tooling or dies that are customized to a given product. AM is seen to be a crucial element of this new trend. “Stereo Lithography (STL)” files are created by converting "Computer-Aided Design (CAD)" files for use in additive manufacturing processes. The CAD modeling system utilized is CATIAv5r18 from Dassault Systems, and the modeling approach employed is detailed. This article emphasizes is on theoretical strategies for the creation of analytical methods for figuring out the mechanical characteristics of AM-MM structures.). This led to the usage of composite mechanics in the analytical approach. The determination of various stiffness parameters (Modulus and Poisson's ratio) of AM-MM structures based on the constituent material characteristics is covered in this chapter. Additionally, the suggested analytical model will help analyze the behavior of MM structures under various loading scenarios. And also this work explains how to numerically analyze an AM-MM structure using the FEA programmer ABAQUS 6.10®.

Keywords: Additive Manufacturing, Computer-Aided Design, Analytical and numerical assessment, Multi-material structure

I. INTRODUCTION

Additive manufacturing (AM) is a key manufacturing technique that creates products by adding material in layers rather than removing it [1]. Using three-dimensional computer-aided design (3D CAD) data, AM creates physical models, functioning prototypes, or functional parts. It functions by combining CAD modeling, laser, photochemistry, sintering, and control drives. When creating things from 3D model data, AM is the process of mixing materials to build items, typically layer by layer, in contrast to subtractive manufacturing techniques like conventional machining [2]. The main benefit of AM is the immediate manufacture of a 3D CAD system-created model without the need for process planning. On the other hand, traditional manufacturing necessitates a close investigation of the part geometry to ascertain things like the equipment and methods that must be used, the sequence in which various features can be developed, and so on [3]. The ability of additive manufacturing (AM) technologies to create complex items without the need for moulds provide designers with a chance to construct MM structures with new designs that would otherwise be challenging with conventional manufacturing procedures. High levels of geometrical complexity can be manufactured with little or no limitations [4]. The AM method also provides a variety of options, such as the ability to create structures with spatial material heterogeneity (discrete type MM structures), directly assemble multi-component assemblies, and create structures with varying densities and compositions of materials. The apparatus Additive Manufacturing (AM process) and materials utilized in this thesis are described in depth in this paper. A detailed description of the design and operation of the discovered AM process (poly jet 3DP), as well as its distinctive capacity to process various materials, is also provided. Also described are the experimental methods used for the tensile, flexural, and shear tests over the AM-MM structure [5]. To explore the surface morphology of broken surfaces, specimen preparation for SEM is explained at the conclusion.

II. RELATED WORKS

The study [6] proposed an effective approach for solving continuous structure optimization issues including resilient multi-material topology under unpredictable loads. The research [7] focuses on the process of the adherend bending stiffness on joint rotation and ultimate joint strength and proposes a computational technique for predicting adhesive joint reaction and failure in multi-material systems. The research [8] offered a computational technique for multi-material corners that provides precise estimates of generalized stress intensity factors using relatively coarse and homogenous discretization. The research [9] proposed a reliable numerical method for choosing cold spray process parameters to create coatings and freestanding porous metal objects with controlled porosity, connectedness, and strength. The research [10] proposed a "Direct Digital Manufacture" (DDM) component composed of composite, ceramic, metal, plastic, and leaf elements are each key in one use of Additive Manufacturing (AM) in aerospace production. The paper [11] proposed that multi-material/multifunctional design and production capabilities have superseded single-material printing in laser-metal additive manufacturing. The article [12] provided a Printing on many materials is still in its infancy of research, they accept the potential to significantly affect a wide range of industries, including structural composites, electrical gadgets, energy storage and production, and healthcare. The study [13] provided a complete analysis of recent advancements with it polymeric composite materials, the powder preparation of these materials now Additive Manufacturing (AM), and the applications, and applications of their printed products. The research [14] presented the "3D Plasma-Metal Deposition" (3DPMD) approach as a cutting-edge "Additive Manufacturing" (AM) technology for multi-material components. The paper [15] suggested a combining numerous materials are now possible without the need for assembly, leading to new ways of manufacturing and construction.

III. METHODS AND MATERIALS

The optional additive manufacturing process

The goal of ongoing research into additive manufacturing (AM) is to create complex-shaped parts with different materials that can perform similarly to components made using traditional manufacturing methods. Few AM methods are now able to produce parts made of various materials. Using photopolymer resins like Stereocol, which change color when subjected to curing light from the SLA machine laser, stereo lithography has been utilized to fabricate parts with distinct types of multiple materials (Gibson et al 2006). As in the typical situation when one nozzle is used for part material and the other is used for support material, the secondary nozzle has been employed in the FDM process to manufacture different features for parts in addition to building supports. However, the FDM technique has nozzle size restrictions that prevent it from being used to fabricate MM structures with high dimensional accuracy. The fabrication of MM structures using powder-based AM techniques such as 3D Printing (3DP) or Selective Laser Sintering (SLS), where the untreated (unglued in the case of 3DP and unsintered in the case of SLS) powder acts as the support or barrier for the fabricated part, which must then be removed and infiltrated by secondary material. But these AM procedures need the right post-processing techniques. The poly jet 3DP method includes advantages such as high dimensional accuracy, micron-level layer thickness, and the ability to produce parts with precise details (Vaupoti et al. 2006). It also offers significant process flexibility in terms of the variety of materials that may be treated. The Polyjet 3DP process allows the fabrication of regions with various qualities inside a layer by simultaneously ejecting numerous materials according to the material designated for the specific region in the CAD model. As these machines have material deposition mechanisms with multiple nozzles to deposit multiple materials within a layer, they are suitable AM processes for the objective set (discrete type MM structure with a specific position and orientation of secondary material). FDM and Polyjet 3DP machines also work well for this objective. However, the materials used for FDM multi-material part production typically lack distinguishable mechanical characteristics. A wide range of materials, from elastic and ductile to rigid and brittle in behavior, are supported by the Polyjet 3DP machine. Therefore, the Polyjet 3DP AM approach has been chosen over the other AM techniques for the manufacturing of MM structures.

3D Printing with Polyjet

As shown in Figure 1, the Polyjet 3DP process fabricates MM structures by jetting photo-curable polymer resin through inkjet nozzle heads. A set of white color nozzles delivers one type of photopolymer material, while a set of black color nozzles delivers a different type of photopolymer material. There are eight printing inkjet heads in a poly jet print head block. Each material has two perfectly timed printing heads, with the remaining four heads being used for the support material. Every one of the 96 nozzles in every print head is controlled by a slice of the MM structure CAD model. Model materials are sprayed according to their location from predefined nozzles, giving complete control over the structure of the material. With this method of manufacturing, two polymer materials are deposited as they were designed in CAD onto a part and built up layer by layer until the part is finished. After being jetted, each multi-material photopolymer layer is immediately exposed to UV light to cure it. This creates a cured multi-material structure that can be handled and utilized right away without further post-curing operations. By using water jetting and your hands, you may quickly and simply remove the gel-like support substance, which was created especially to hold intricate geometries.

Figure 1: Polyjet 3DP head assembly block schematic images

Selection of materials

Photopolymers, which are polymeric materials sensitive to light and solidify when exposed to UV light, are the materials utilized in the poly jet 3DP process. A wide variety of materials, including stiff plastic, rubber-like materials, and opaque and transparent materials, can be processed using the Polyjet 3DP method ((PolyJet materials data sheet, 2015). Although the precise characteristics of these materials, including their physical, chemical, and a few mechanical characteristics, are not known, they were identified by the machine supplier's trademark names, such as Vero White, Durus White, Tango, etc. Selecting the right combination of materials from this variety will change the mechanical qualities of the multi-material item produced with poly jet 3DP. New values for impact, tensile, and flexural strength will be produced by these combinations. Materials with unique mechanical properties have been examined for the production of MM structures among the numerous polymer materials that can be processed by the poly jet 3DP method. Durus White and Vero White materials with mechanical qualities similar to Acrylonitrile Butadiene Styrene (ABS) and Polypropylene (PP), respectively, have been taken into consideration for the manufacture of AM-MM structures. In the production of fit and functional parts, living hinges, and moulds, durus white is typically employed.

Wall and layer thickness

The wall thickness in the AM process is the separation between neighboring surfaces of the part in the XY plane of the part build table, as shown in Figure 3. The term "layer thickness" describes the distance in the Z-direction between two adjacent layers. Many process variables used in the production of MM structures are compiled. For the manufacturing of multi-material structures, the poly jet 3DP process's minimum layer thickness of 30 m is taken into consideration. The minimum wall thickness will, however, affect the shape and size of the feature that needs to be manufactured, particularly the reinforcement's shape and size in AM-MM structures. AM-MM structures are orientated so that the longitudinal cross-section of the reinforcement is created layer by layer in the XY plane.

Figure 2: The minimal wall thickness for the (a) circular feature and (b) square feature was determined using a VMS picture of a specimen.

The fabricated features were examined using a video measurement system, and it was found that the square shape feature exhibits a much clearer contour than the circular shape feature at the minimum dimensions (0.6mm width for square shape reinforcement and 0.6mm diameter for circular shape reinforcement). Due to the 0.5mm nozzle diameter in the print head, which will deposit photopolymer resin not less than 0.5mm in the XY plane, the circular shape feature contour is inaccurate by at least one dimension (0.6 mm), whereas the longitudinal cross-section width of the circular shape reinforcement at the XY plane is 0.6 mm only at its mid-span and is less than 0.6 mm in other layers.

Part orientation

Part orientation is the positioning of various MM structures in a part-built table with the least amount of support material and the quickest manufacturing time possible. Additionally, it has been demonstrated that part orientation causes variation in the mechanical characteristics of AM parts and systems. Figure 3 illustrates the part orientation taken into account for the manufacturing of AM-MM structures, where structures are parallel to the XY plane. The strength of the manufactured AM-MM structure is higher in this orientation than in other orientations, according to research, hence this orientation has been finalized (i.e. parallel to YZ or XZ plane). Machine volume cannot fit all of the AM-MM structures in a single build since there will be a significant number of them to create. Thus, three AM-MM constructions are constructed in eight hours, each lasting more than two and a half hours, with the remaining time being used for setup and equipment cleaning.

Figure 3: Platform designed with a partial orientation

Support structure

There are no overhanging or undercut features in AM-MM structures that are being examined for production. But to remove the constructed structures off the platform for building machine parts, a support structure is needed at the base. A low-grade gel-like substance is utilized as a support framework for this reason. With the aid of a gel-like support structure, AM-MM structures may be removed from part-build platforms and cleaned with a water jet without causing any damage to the component. The support structure is automatically constructed with the help of an inbuilt algorithm in machine-associated software (Objet Studio), which is an interface between.STL model and machine.

Mechanical properties characterization

Following the fabrication of AM-MM structures with different orientations, stacking arrangements, and volumetric reinforcement percentages, these structures are tested under various loading conditions to determine their mechanical behavior. Additionally, design, analytical, and numerical calculations will be made using the experimental test data. The majority of real-world applications will put MM structures made by the AM method to various testing protocols for evaluation. To assess the mechanical properties of the AM-MM construction, experimental tests like tensile, flexural, and shear have been carried out. Because several material qualities depend on the cross-sectional area, it is crucial to pay attention to the dimensions of test specimens made from AM-MM structures. Before conducting a physical test, the dimensions of the AM-MM structure specimen are measured for all sorts of tests. The thickness and width of the test specimen for the AM-MM structure are crucial dimensions. A batch of specimens (N = 3) is created via the poly jet 3DP procedure for each test. The steps taken to conduct the experiments and equations used to generate the data required for the analytical derivation of cross-laminated timber (CLT) and the numerical model are explained in the following subsections.

Tensile test

The tensile test is used to assess the axial load resistance of different AM-MM constructions. Tensile strength tests are performed using an Instron-3362 testing machine with a crosshead speed of 5 mm/min on AM-MM structure specimens by ASTM D638 Type IV standard. The ASTM D-638 test is typically used to measure the tensile properties of both unreinforced and reinforced polymers. Equations (1) to (4) can be used to compute tensile parameters such as ultimate tensile strength, percentage of elongation, and tensile modulus using the curve produced by the tests (3). The test is stopped once a complete fracture of the AM-MM structural test specimen has taken place. The specimen of the cracked AM-MM structure is then taken out and maintained for inspection.

$\varepsilon=\delta ll$ (1)

$\varepsilon=\delta ll$ (2)

$E=\sigma\varepsilon$ (3)

Two 350 Ohm strain gauges are installed on the test specimen's center section during the tensile test to quantify displacement. From these values, the engineering longitudinal and transverse strains are calculated. For an AM-MM structure test specimen, Poisson's ratio can be computed**.**

Shear test

The ASTM D7617 standard, which is typically used to evaluate the shear properties of plastics, is the basis for measuring shear strength. The load is applied to a UTM machine at a speed of 5 mm per minute (continuous strain rate) and at a typical room temperature. The specimen is centered in a U-shaped clamp that contains slots on both sides, and the top pedestal is hydraulically lowered until it is just over the specimen's surface. Next, the center loading nose is lowered at a pace of 5 mm per minute. Following the test specimen's fracture, the force is halted. The ultimate shear strength, also known as the highest shear stress that the specimen could withstand during a shear test, is computed using the load-displacement curves that are recorded during testing (4). The equation is used to determine the maximum deformation of the material under shear force (5). The equation is utilized to determine shear modulus (G) (6).

$\tau ult=PultA$ (4)

$\gamma=\delta ll$ (5)

$G=\tau\gamma$ (6)

Flexural test

Flexural strength tests are performed utilizing an Instron-3362 testing machine with a three-point bend fixture and a crosshead speed of 5 mm/min over produced AM-MM structures following ASTM D790 standard. The dimensions of the test specimens are made following ASTM. The dimensions of the test specimens are made following ASTM D790. The bottom supports of the three points bend test jigs are spaced apart 16 times the thickness of the specimen by ASTM standards.

The flexural load is applied until the stress created by the flexural loading reaches saturation. Using machine-related software, the load and displacement curve is continually acquired. These curves are used to calculate the flexural stress and strain, which are used to calculate the flexural modulus. Equations (7), (8), and (9) are used to calculate the flexural stress, strain, and modulus.

$Flexural\ stress\ \sigma ult=3PultL2bd2$ (7)

$Flexural\ strain\in=6DdL2$ (8)

$Flexural\ Modulus\ Eb=L3m4bd3$ (9)

Analysis of the surface morphology of fractures

Scanning Electron Microscopy (SEM) was used to assess the fracture surfaces of AM-MM structures with and without reinforcement to study the fracture morphology. A VEGA3 TESCAN model is used for SEM, and a 30 kV electron voltage is used. Before performing a fractographic examination, a thin slice of the fractured surface is produced and sputter-coated with a thin layer of gold. SEM Typically, fractography images provide information on the failure mechanisms underlying crack propagation, potentially illuminating the site of toughening and the linkages between the orientation of the reinforcement and its properties from a microscopic perspective. A fracture specimen is also subjected to a macroscopic study using a video measurement system (VMS).

IV. RESULT AND DISCUSSION

Stress-strain relationship

MM structures behave mechanically differently than those traditional engineering materials. The homogeneous and isotropic properties characterize the majority of engineering materials. When a substance is homogenous, it has consistent qualities throughout its structure, whereas an object that is isotropic exhibits the same behavior in all directions. Contrarily, MM structures are frequently both orthotropic and heterogeneous (i.e., non-homogeneous) (non-isotropic). Orthotropic refers to a material's behavior that differs in three mutually perpendicular directions, while heterogeneous refers to non-uniform qualities throughout the material structure. Under pure axial and shear loads, the free-body diagram of various types of materials is shown in Figure 4.

Figure 4: Response of different material types under pure shear and uni-axial normal loading

When it comes to MM structure, Young's Modulus in Longitudinal Direction is denoted by equation (10).

$E1=\sigma1\varepsilon1$ (10) In a transverse direction, Young's Modulus is given in equations 11 and 12.

$E2=\sigma2\varepsilon2\&E3=\sigma3\varepsilon3$ (11) Whereas

$\varepsilon1=\Delta x1x1,\varepsilon2=\Delta x2x2\&\varepsilon3=\Delta x3x3$ (12) The direction of the strain created in the orthotropic MM structure is given by equations (13),(14), and (15).

$\varepsilon1=\sigma1E1-\vartheta21\sigma2E2-\vartheta31\sigma3E3$ (13)

$\varepsilon2=\sigma2E2-\vartheta12\sigma1E1-\vartheta32\sigma3E3$ (14)

$\varepsilon3=\sigma3E3-\vartheta23\sigma2E2-\vartheta13\sigma1E1$ (15)

Similar shear stress is produced in the appropriate direction by equations 16, 17, and 18.

$\gamma23=\tau23G23$ (16)

$\gamma13=\tau13G13$ (17)

$\gamma12=\tau12G12$ (18)

To determine Hooke's law stress-strain connection at a point in an x-y-z orthogonal system, equations (13) to (18) are combined in matrix form.

$[\ \varepsilon1\varepsilon2\varepsilon3\gamma23\gamma13\gamma12]=[\ 1E1-\vartheta21E2-\vartheta31E3000-\vartheta12E11E2-\vartheta32E3000-\vartheta13E1-\vartheta23E21E3\ 0000001G230000001G130000001G12]\ [\ \sigma1\sigma2\sigma3\tau23\tau13\tau12]$ (19)

In MM structures, single layers are taken into account for the micro-mechanics approach; therefore the thickness in the third direction is relatively less than the dimension in the first and second directions. Therefore, for the Equation, the plane stress condition (i.e.,$\sigma3 = \tau13= \tau23 = 0$) is used (19).

$[\varepsilon1\varepsilon2\gamma12]=[\quad 1E1-\vartheta21E20\vartheta12E11E20001G12]\ [\sigma1\sigma2\tau12]$ (20)

This condensed matrix equation (20) demonstrates that five constants ($E1$, $E2$,$\vartheta12$,$\vartheta21$) are necessary for valuing the stress-strain behavior of MM structures.

$\vartheta21E2=\vartheta12E1$ (21)

Thus, the number of constants needed to predict the stress-strain behavior is now reduced to four by knowing values $E1$, $E2$, $\vartheta1$, and $\vartheta2$.It is more practical to rewrite Equation (21) in the inverse form (i.e., the stress in terms of strain) for the majority of the following analysis.

V. CONCLUSION

This paper covers the optional additive manufacturing process and 3Diamensional printing with Polyjet. This article also covers the fabrication and mechanical properties of characterization. It covers the AM-MM structure and Scanning Electron Microscopy (SEM). Fabricated AM-MM structures are characterized under a variety of circumstances, including tensile, shear, and flexural loads, with different positions, orientations, and volumes of reinforcement. In addition, experimental, analytical, and numerical methods are suggested in chapters five and six to forecast the mechanical characteristics of AM-MM structures under various loading circumstances. The findings of experiments have been used to thoroughly validate the viability of applying analytical methods. The largest divergence of the result based on the analytical method concerning the experimental method, other than AM-MM constructions with transverse reinforced layers, is reported to be within 8.48%. The mechanical response of the AM-MM structure has been simulated using a numerical method based on the composite layup module of the ABAQUS CAE programmer, and it has been assessed using experimental data. Except for AM-MM structures that only include transverse reinforced layers; there is a 10.75% difference between the results of numerical simulation and experimental results.

Data availability
Not applicable.
Code availability
Not applicable.
Declarations
Ethics approval
Not applicable.
Consent to participate
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Consent for publication
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Conflict of interest
The authors declare no competing interests.

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