INTERGRATED DESIGN OPTIMIZATION SCHEME FOR FIBER REINFORCED ADDITIVE MANUFACTURING

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ABSTRACT

Fiber reinforced additive manufacturing (FRAM) is a technology which has grown in popularity over recent years. FRAM refers to a typical FDM additive manufacturing process which can imbed various reinforcing fibers. FRAM couples advantages of both additive manufacturing and composite materials; creating products of complex geometry which are lightweight and strong when compared to alloy counterparts.

This work aims to couple the benefits of FRAM technology with design optimization. By considering FRAM as an integral basis for the design optimization, components are produced which effectively consider the complex material properties of the composite. A material model was developed specific to FRAM materials; used to initialize the optimization and verify results. The FRAM optimization process begins with a composite sizing optimization of a shell element model. The sizing optimization is used to identify dominant ply orientations to be utilized when printing the component. Material properties and failure criterion are populated based on the optimized ply orientations and printing parameters of the composite. Topology optimization is used to optimize a 3D design space and create a topology of the FRAM material.

Results were produced using optimization problem statements to minimize compliance and mass of the academic model. The problem statement showcases the lightweight and structurally optimized designs which are obtained by implementing FRAM. When compared to metallic topology optimization results, the increased design freedom and mechanical properties of the FRAM material improve the response of the objective function. An academic model utilizing FRAM achieved a 20% improvement in the compliance design metric when compared to an equal-mass, aluminum academic model.

1. INTRODUCTION

Additive manufacturing (AM) has seen major developments in the past decades. The technology has seen increased implementation in industry, capability of hardware, availability of materials, and focus in academia. In recent years, fiber reinforced additive manufacturing (FRAM) has increased the capabilities of typical fused deposition (FDM) printing. FRAM couples aspects of AM with composite materials. The process prints a component in a typical FDM process while imbedding various reinforcing fibers. The result is a layered, composite material which retains many advantages of AM. In many cases, AM materials are disqualified in structural applications because of the weaker polymeric properties, relative to metallic alloys. The addition of composite fibers improves the material properties of the printed components to provide a competitive alternative to metallic components.

Topology optimization (TO) is a design optimization tool which is used to optimize specified performance metrics while abiding to specified constraints. TO is a popular optimization tool and can be applied to a variety of problem statements. TO uses finite element analysis (FEA) to evaluate design performance. TO and FRAM synergize particularly well because the FRAM manufacturing process can support the complex design geometries which are typically produced by TO.

The objective of this work is to incorporate FRAM materials into a TO-based design optimization problem. The resulting component utilizes benefits of the FRAM process and has an optimized material distribution of the FRAM material, specifically.

2. MATERIALS AND METHODS

2.1 FRAM Materials

FRAM materials are classified as a typical FDM AM process which incorporates composite fibers into the printing process. Different types of fibers can be incorporated; carbon fiber, glass, and Kevlar are popular options. In addition to the fiber material, either short, randomly oriented fibers (S-FRAM) or continuous, oriented fibers (C-FRAM) can be implemented.
This work will specifically focus on the implementation of continuous carbon fibers in a proprietary nylon matrix.
The FRAM printing process produces a quasi- laminate composite. Typical to FDM, the component is built in ascending layers. Each layer is composed of a proprietary nylon matrix which has continuous fibers incorporated. Fibers may be oriented at any orientation or sequence of orientations. The aligned fibers cause a single print-layer of material to be highly anisotropic. Depending on orientations utilized throughout the whole component, the bulk material can range from highly anisotropic to quasi-isotropic.

2.2 Topology Optimization (TO)

Topology optimization is a design optimization tool be used to determine optimum allocation of material. The term *optimum* is relative to the specific goals of the optimization. The optimized design is with respect to a design space, specific loads/boundary conditions, objectives, and constraints.

TO is based on finite element analysis (FEA); the design space is divided into finite elements. The method uses a density-based approached coupled with a penalization method to determine optimal existence of material in the discretized design space.

2.3 Laminate Optimization

Laminate optimization is a design optimization tool which is typically utilized on traditional laminated composites. Laminates can be optimized in a variety of ways including free-size, discrete-size, and stacking sequence optimization. In the context of FRAM materials, not all types of laminate optimization are applicable and/or physically meaningful.

The work uses laminate sizing optimization to identify ply orientations which are significant in the loading scenario(s) of the component. Dominant ply orientations are selected to populate the material model.

2.4 Orthotropic Material Model

FRAM material have anisotropic material properties. Selection of ply orientations can cause major variance of the material properties. To accurately model the printed components, an orthotropic material model was developed to consider properties of the bulk material.

The model creates a global compliance matrix to model the bulk material. In-plane, ply properties are populated based on reported values [1][2][3].

The baseline, 0°, compliance matrix can be rotated to reflect ply orientations:

$$[S]=[R]^T[S'][R] \tag{1}$$

Using the rotation, compliance matrices can be populated for all expected ply orientations. The compliance matrices can be summed based on global volume fraction of each ply orientation:

$$[S_G]=V_{f,\theta_1}[S_{\theta_1}]+V_{f,\theta_2}[S_{\theta_2}]+V_{f,\theta_n}[S_{\theta_n}] \tag{2}$$

Where $\theta_{1\ldots n}$ is the ply orientation of the print layers. From the global compliance matrix, key orthotropic material properties can be extracted for the bulk, printed material. Notably E_1, E_2, E_3, G_{12}, G_{23}, G_{13}, ν_{12}, ν_{23}, ν_{31} for the Optistruct solver.

3. RESULTS AND DISCUSSION

3.1 Modelling

Topology optimization will be used to optimize a particular component which is a candidate for FRAM. A basic problem statement will be used, as follows:

Minimize:

$$C(\rho)=U^TKU \tag{8}$$

Subject to:

$$K(\rho)U=F \tag{9}$$

$$\frac{V(x)}{V_0}\le f \tag{10}$$

$$\rho_{\min}\le\rho_e\le\rho_{\max} \tag{11}$$

The optimization statement works to minimize compliance, C(ρ), subject to a maximum volume fraction, *f*. K is the global stiffness matrix, U is the displacement vector, and F is the force vector. ρ represents element density which can vary from 0, signifying void, to 1, signifying full density material.

The compliance of a component is the sum of strain energy; it can be considered as the inverse of stiffness. By minimizing compliance subject to a specified volume fraction, the optimization is creating a lightweight design with topology for maximum stiffness.

3.2 Academic Model

To illustrate the described methods, a MBB beam model will be optimized. The MBB beam will be subject to the typical loading case:

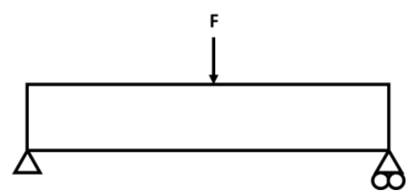

FIGURE 1: MBB BEAM LOAD AND BOUNDARY CONDITION

Four models will be considered for the described topology optimization. The study examines two topology optimization problems which utilize the FRAM technology. The two FRAM examples illustrate the described optimization method. In addition, two equal-mass aluminum topology optimization problems are examined to provide a baseline of typical TO and materials implementations. Comparison to the aluminum baseline models quantifies the improvements garnered from implementation of the proposed optimization process.

3.3 Unconstrained Topology Optimization

3.3.1 Aluminum Baseline Model

To provide a baseline, topology optimization is used to optimize an aluminum beam.

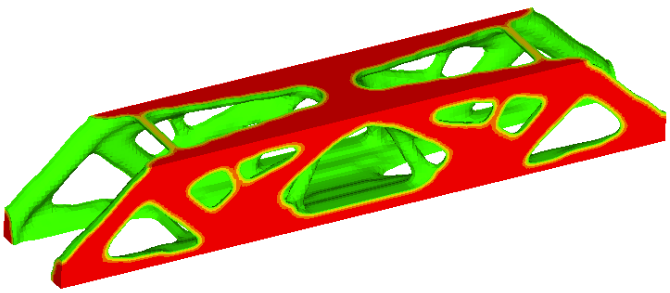

FIGURE 2: ALUMINUM TOPOLOGY OPTIMIZATION RESULT

TABLE 1: ALUMINUM TOPOLOGY OPTIMIZATION PARAMETERS

E	78.3 GPa
ν	0.33
ρ	2.8 g/cm^3

Volume Fraction	20%
Compliance (mJ)	1706
Weight (g)	26.6

The result, constrained to a mass of 26.6 g, completes optimization with a compliance of 1706 mJ.

3.3.2 FRAM Model [0 5 10 -10 -5 0]

The optimization scheme begins by determining the ply orientations for the FRAM component. Dominant ply orientations are identified in a shell model of the MBB geometry. The following results are obtained, sizing potential ply orientations between 0.1 mm – 1.0 mm.

TABLE 2: PLY ORIENTATION RESULTS

Ply Orientation (°)	Thickness (mm)	Ply Orientation (°)	Thickness (mm)
0	1.00	0	1.00
5	1.00	-5	1.00
10	1.00	-10	1.00
15	0.19	-15	0.78
20	0.10	-20	0.18
25	0.10	-25	0.16
30	0.10	-30	0.10
:	:	:	:
90	0.10	-90	0.10

Ply orientations which retain the maximum representative thickness in the sizing optimization are selected. Based on ply orientation optimization results in Table 2, the dominant ply orientations are the 0°, ±5°, and ±10°. This result is intuitive because of the simple single-load case applied to the MBB beam. The optimization result shows ply orientations which are highly oriented along the length of the beam; with some slight variance to mitigate in-plane, transverse deflection. The optimization will continue with a [0 5 10 -10 -5 0] stacking sequence for the FRAM material.

Using the described orthotropic material model, the material properties of the FRAM material are described. The material properties are used to populate a typical 6x6 compliance matrix to define the orthotropic material as solid elements.

TABLE 3: [0 5 10 -10 -5 0] MATERIAL PROPERTIES

E_1	57.4 GPa	**G_{13}**	4.9 GPa
E_2	4.4 GPa	**ρ**	1.4 g/cm^3
E_3	4.3 GPa	**ν_{12}**	0.43
G_{12}	5.3 GPa	**ν_{23}**	0.37
G_{23}	4.2 GPa	**ν_{31}**	0.02

Topology optimization is used to optimize the solid structure of the [0 5 10 -10 -5 0] FRAM material. The following topology is obtained:

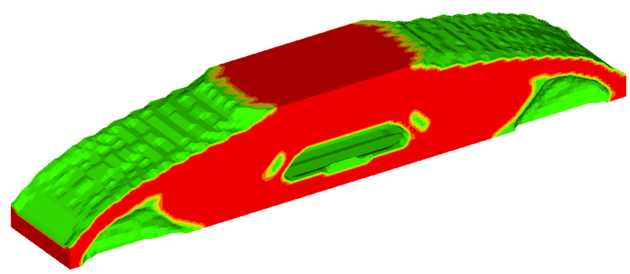

FIGURE 3.1: FRAM TOPOLOGY OPTIMIZATION RESULT (VF 40%)

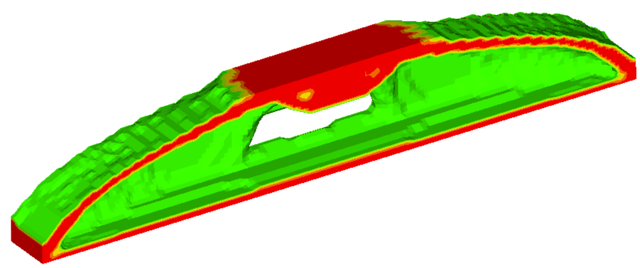

FIGURE 3.2: CROSS SECTION OF FRAM TOPOLOGY OPTIMIZATION RESULT (VF 40%)

TABLE 4: FRAM (VF 40%) OPTIMIZATION PARAMETERS

Volume Fraction	40%
Compliance (mJ)	1590 (-7%)
Weight (g)	26.6

The FRAM result shows a 7% reduction in compliance compared to the equal-mass aluminum design. Both designs are initialized with an identical "blank-slate" design space. Following the optimization, both examples have an unconstrained, optimal topology. The FRAM result, however, shows an improvement in the design metric, compliance. This result is a consequence of the ply orientation optimization. Implementing an optimization procedure to optimize the ply orientations, thus the material properties, of the FRAM material allows the FRAM result to out-pace the metallic counterpart. Polymeric materials which are typically utilized in additive manufacturing processes would not posses the ratio of density-elastic modulus to compete with an unconstrained metallic design.

3.4 Manufacturable Designs

Overall, the CFRP result shows reduced compliance at equal mass when compared to the aluminum design. Manufacturability, however, is not considered. The design freedom available from additive manufacturing would allow a nearly identical topology to be produced, physically, for the FRAM model. The aluminum model, however, would require manufacturing constraints to produce a design which could be reasonably produced. With increased manufacturing constraints comes a decrease in design freedom and consequently a decrease in performance. Metallic materials typically experience this decrease in performance due to practical manufacturing considerations.

3.4.1 Aluminum Manufacturable Model

The following aluminum result is created using the same topology optimization statement and an extrusion constraint:

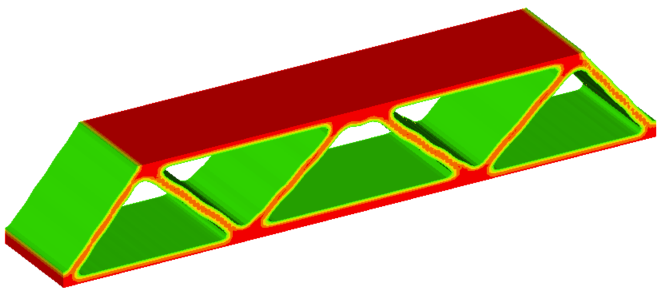

FIGURE 4: ALUM. OPTIMIZATION RESULT (EXTRUSION)

TABLE 5: ALUMINUM TOPOLOGY OPTIMIZATION (EXT) PARAMETERS

Volume Fraction	30%
Compliance (mJ)	1440
Weight (g)	39.9

The allowable volume fraction was increased to 30% to allow proper development of the topology with the manufacturing constraint. With a manufacturing constraint, the aluminum result is a reasonable candidate for manufacture.

3.4.2 FRAM Model [0 5 10 -10 -5 0]

To contrast the performance of the aluminum and CFRP, another equal-mass topology optimization of the [0 5 10 -10 -5 0] composite was completed. The volume fraction constraint was increased to 60% to maintain equal mass.

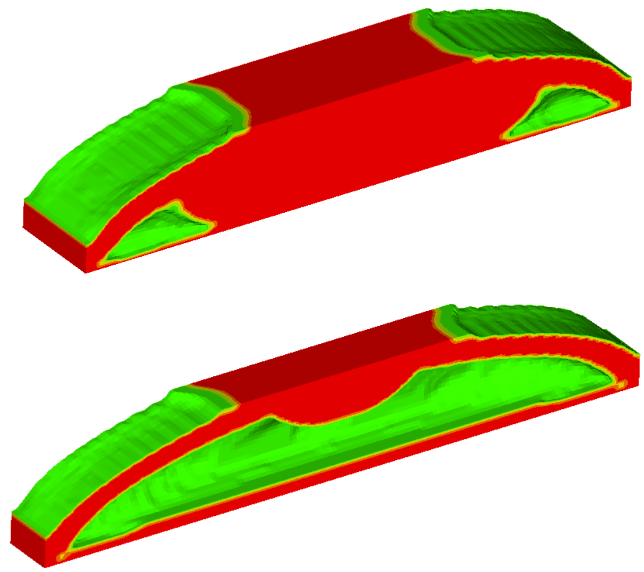

FIGURE 5: FRAM TOPOLOGY OPTIMIZATION RESULT (VF 60%)

TABLE 6: FRAM (VF 60%) OPTIMIZATION PARAMETERS

Volume Fraction	60%
Compliance (mJ)	1152 (-20%)
Weight (g)	39.9

Comparing the manufacturable aluminum topology results against the equal-mass FRAM topology result shows a greater improvement in compliance. Since the FRAM manufacturing process does not reduce design freedom of the printed component, the topology can remain closer to the unconstrained design. The driving factor responsible for the further improvement of the objective function is the maintenance of design freedom. The additive manufacturing process can produce components with complex geometry and minimal divergence from the raw TO solutions. As such, the FRAM models are not subject to aggressive manufacturing constraints. Overall, this relationship allows the optimization process to maintain design freedom and produce designs which represent the optimum topology. Along with the previously described material outpacing, the optimization results of the manufacturable designs utilize the unconstrained design freedom to increase objective function improvements further.

It should be noted that the aluminum and FRAM academic models both have optimized topology. Since the topology of each model is designed based on the same optimization scheme, the models isolate the advantages of FRAM implementation, specifically.

In practical application, typical metallic components do not have optimized topology. The potential of implementing both topology optimization and FRAM present greater potential for light-weighting and improvement of structural performance. In practical applications, the FRAM topology optimization quickly out-perform the aluminum counterpart. FRAM synergizes particularly well with optimization schemes because of the design freedom an engineer can maintain in the topology. The technology offers an advanced material and a greater potential for implementation of design optimization. The implementation of FRAM allows for the unfettered use of design optimization without typical manufacturing limitations.

4. CONCLUSION

This work aims to implement the use of fiber reinforced additive manufacturing (FRAM) into an optimization scheme. The implementation of a specific orthotropic material model allows the unique properties of FRAM components to be effectively included into topology optimization. Optimized, academic models are compared to show distinct, quantitative advantages associated with use of FRAM. FRAM synergizes particularly well with topology optimization and presents opportunity to drastically increase the mechanical performance of typical alloy components. The work aims to show that FRAM not only offers a suitable replacement, but an improved replacement to metallic alloys in design optimization.

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