MULTI-MATERIAL TOPOLOGY OPTIMIZATION FOR COMPOSITE METAL AIRCRAFT STRUCTURES

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ABSTRACT

This paper investigates an optimization routine for lightweight composite-metal hybrid aircraft structures. This routine is developed based on two existing topology optimization approaches, Moving Morphable Components (MMC) and level set method updated by a reaction diffusion equation. The proposed method overcomes the weakness of conventional multi-material optimizers by introducing some rules of material distribution, that enhance the manufacturability of the optimal structure. It is achieved by optimizing the main structural frame using uniform-width components first, leaving the joints as void together with the remaining design domain, and following by a conventional topology optimization using single-material level set approach. A commonly used beam model is optimized to demonstrate the key ideas of the proposed routine.

1 INTRODUCTION

Topology optimization (TO) is a computational method to output a structure which satisfies multiple design constraints while maximising or minimising the objectives. This technique is widely used in the conceptual design stage since it does not require a pre-configuration of the product. Numerous topology optimization methods have been introduced and intensively studied over the past two decades, including the famous SIMP (Solid Isotropic Material with Penalisation), ESO (Evolutionary Structural Optimization) and Level Set Method [1]–[3]. As a variant of homogenization method, SIMP successfully achieve topological optimum by setting the material density as the design variable. However, the main drawback of density based method is the physical interpretation of intermediate densities. Although a model consisting of repeated lattice cells which have the same topology but different sizes is introduced by Brackett et. al. [4], explaining the physical meaning of low density elements. It is still difficult to manufacture such tiny lattice with present commercial manufacturing technologies. In contrast, level set based method can output structures consisting of only discrete elements which significantly increase the manufacturability of the final design, which is highly suitable when dealing with Fibre Reinforced Polymer (FRP) composites.

However, most of the well-known TO methods are restricted to single-material optimization. This essentially limits the optimization algorithm to accommodate more objectives, restricts the choices available to designers. For instance, in the work of Wang et. al. [5], a three phase (two materials and void) optimal structure with adjustable material ratios is obtained. Designers can trade off the overall cost and the stiffness by adjusting the volume ratio between two materials. In recent years, multi-material topology optimization has received considerable research attention. Several multi-material topology optimization methods have been introduced over the past decades, such as the Alternating Active-Phase Algorithm [6]. Among those methods, level set based approaches for multiple phase structural optimization problems draw much attention because explicit expression for the boundaries that can be achieved. Wang et al. [7] first introduced the 'color' level set for compliance minimization problems. The so called Multi-Material Level Set (MM-LS) method was then proposed by Wang et al. [5], developing a model where N+1 phases are expressed by N level set functions. Cui et al. [8] proposed a similar MM-LS model but solved it using a reaction diffusion equations.

Most of the existing topology optimization approach, however, describes the structure in an implicit way (i.e. a set of elements). This restricts the control of the geometry of the optimized structures. In order to take advantage of the merits of both shape optimization (where geometric parameters are considered as the design variable and a pre-configuration is needed) and topology optimization (where the topology of the optimum is not required as the input), Zhang et. al. [9] proposes the so called Moving Morphable Components (MMC) method, which allows designers to control the structural type while conducting topology optimization. Due to the geometry parameters being exclusively embedded in TO, MMC shows promising results from manufacturing point of view of FRP composites.

In aerospace industry, there is a growing interest in FRP composite materials due to their higher specific strength and stiffness stronger relative to conventional aluminium alloys. One of the challenges, however is the difficulty in manufacturing complex structures. Where aluminium alloys are capable to be formed into a variety of geometries, FRP composites perform best when design in simple flat or linear structures. Therefore discovering the most ‘efficient’ structure, the FRP composites component must be a geometry that is simple while metallic materials make take the form of the remaining complex structure. To solve this problem, the sole usage of single-material optimization method (including classic TO and MMC) is obviously insufficient. Current multi material optimizations are also ineffective as there is a need to regulate for composite geometrical constraints.

In this paper, MMC and MMLS optimization routines are selected to develop a new optimization routine to design an optimal composite-metal hybrid structure.

2 METHOD AND DISCUSSION

2.1 Model description

In this paper, a commonly used cantilever beam with the root full fixed on the left, and a unit downward force applied at the center of the tip on the right, as shown in Figure 1.

Figure 1 The model of a cantilever beam used as the design domain

2.2 Multi-Material Level Set (MMLS)

Using MMLS, composite and aluminum materials are expressed explicitly by two level set functions ϕ^1 and ϕ^2, where ϕ^1 is the combined set of two materials and ϕ^2 represents only the metal regions. Element sets occupied by two materials are thus expressed as:

$$\begin{cases} \phi^{Composite} = \phi^1 \backslash \phi^2 \\ \phi^{Aluminum} = \phi^2 \end{cases} \tag{1}$$

With the help of Heaviside function $H(\phi)$ [10], [11], the elastic modulus $D_{(x,\phi)}$ at arbitrary computational point x can be calculated by:

$$D_{(x,\phi)} = H(\phi^1)[(1 - H(\phi^2))D^1 + H(\phi^2)D^2] + (1 - H(\phi^1))D^{void} \tag{2}$$

Where D^1 and D^2 denote the Modulus of selected composite and aluminum respectively, and D^{void} is a small value representing the elastic stiffness of void elements.

The topology optimization problem is formulated as follows:

$$\begin{cases} \underset{\phi^i}{inf} \quad F = \int_D \varepsilon(u): D(\phi): \varepsilon(u) d\Omega \\ s.t. \quad G^i = \int_{\Omega^i} d\Omega^i - V_{max}{}^i \leq 0 \\ \quad \int_D \varepsilon(u): D(\phi): \varepsilon(v) d\Omega = \int_\Gamma f v d\Gamma \\ \quad -1 \leq \phi^i \leq 1 \end{cases} \tag{3}$$

Where F denotes the compliance, ε denotes the strain, Ω denotes the material domain. G^i is the constraint function and $V_{max}{}^i$ is the maximum volume of the ith material. u is the displacement field, v is the virtual displacement and Γ is the boundary of the structure. The topological derivative of the Lagrangian of above problem, $d_t\bar{F}$ is given by:

$$d_t\bar{F}^i = (\sum_i^2 \varphi^i D^i)\widetilde{u_{k,l}}^0 A^i_{klmn} u^0_{m,n} - \lambda^i \tag{4}$$

φ^i is a vector containing location information of the ith level set. $\widetilde{u_{k,l}}$ and λ^i are the Lagrange multipliers and A_{ijmn} is calculated using Poisson's ratio v and Kronecker's delta function δ by:

$$\begin{aligned} A^i_{klmn} = D^i \frac{3(1-v)}{2(1+v)(7-5v)} [&\frac{-(1-14v+15v^2)}{(1-2v)^2} \delta_{kl}\delta_{mn} \\ &+5(\delta_{km}\delta_{ln} + \delta_{kn}\delta_{lm})] \end{aligned} \tag{5}$$

Then the new level set function $\phi^i(x, t+\Delta t)$ is updated from $\phi^i(x,t)$ using the so called reaction diffusion equation by:

$$\phi^i(t+\Delta t) = \boldsymbol{Y^i}/\boldsymbol{T} \tag{6}$$

Where **T** and **Y** are calculated using the interpolation function, **N**, of the level set functions as follows:

$$\begin{aligned} \boldsymbol{T} &= \bigcup_{e=1}^{N} \int_{V_e} \left(\frac{1}{\Delta t}\boldsymbol{N}^T\boldsymbol{N} + \nabla^T N_T \nabla \boldsymbol{N}\right) dV_e \\ \boldsymbol{Y^i} &= \bigcup_{e=1}^{N} \int_{V_e} \left(C d_t\bar{F}^i + \frac{\phi(x,t)}{\Delta t}\right) dV_e \end{aligned} \tag{7}$$

Where N denotes the number of elements and V_e is the volume of an element. For more details on the derivation, the reader is referred to the article[12], [13].

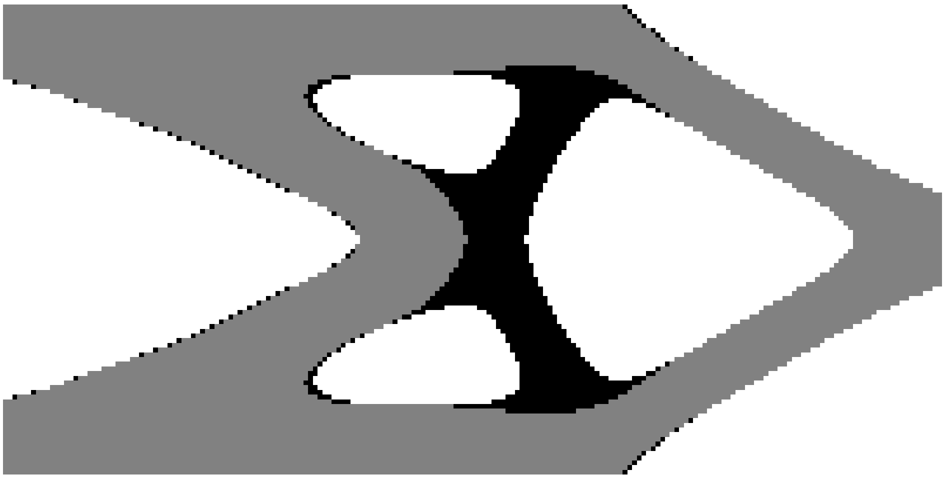

Figure 2 Optimal design obtained by MMLS with E^{Alu}=1 (Black) and E^{Comp}=2.6 (Grey)

Figure 2 shows the obtained structure using MMLS optimization routine. The black region represents aluminum and the grey region represents composite. The volume ratio of composite to metal is approximately 4:1, in order to maximize the usage of composite. As shown in the result, aluminum takes part in some of the load-carrying geometries as well as the coating on the surface. This model is useful when the ratio between materials is the driver of the design. For example, when considering the cost against the stiffness of the structure, MMLS can output the stiffest topology at a certain cost. However, there seems to be a lack of logic in this structure. In other words, instead of simply piling up materials to form the structure, there should be some rules of distribution by which materials can be arranged in the desired way. In this particular problem, there is no constraint on the geometry of the composite. A desired geometry would be a composite-forming truss with metal materials applied at complex regions e.g. joints. Additionally, it is challenging to identify the regions of 'simple' shapes to constraint in the current model. Also, it is unlikely that the explicit description of the region of interest could be found which will significantly ease the operation to apply distribution rules. Therefore, a model which is capable to control the simplicity of the structure and possess explicit descriptions of its components is desperately needed.

2.3 Moving Morphable Components (MMC)

One solution of the problem is the so called MMC model introduced by Guo et. al. [14] which allows control of the shape of each of the candidate components. In this model, N building block components are initially generated and their coordinates of center points, inclination, length and width are set as the design variables. The optimization of the topology of the structure is realized by altering the position (center point) and the rotation (inclination) of each block. Shape optimization is achieved by changing the width and length of each components. The geometry control is embedded in the optimization by assuming all the candidate components are of uniform width. Mathematically, the optimization problem can be described in form of design vectors $D = (D^1, \ldots, D^i, \ldots D^n)$, where D^i contains the topology information of the ith building block, to minimizing the compliance of the structure. The process is formulated as follows:

$$
\begin{aligned}
&\text{Find } D = \left(D^1, \ldots, D^i, \ldots D^n\right), u(x) \\
&\text{Minimize } C = \int_D H\left(\phi^s(x; D)\right) f \cdot u dV + \int_{\Gamma_t} t \cdot u dS \\
&\text{s.t.} \\
&\int_D \left(H\left(\phi^s(x; D)\right)\right)^q E : \varepsilon(u) : \varepsilon(v) dV = \int_D H\left(\phi^s(x; D)\right) f \cdot v dV + \int_{\Gamma_t} t \cdot v dS \ , \forall v \epsilon U_{ad} \\
&\int_D H(\phi^s(x; D)) dV \leq \bar{V} \\
&D \in U_D
\end{aligned}
\tag{8}
$$

$u = \bar{u}$, on Γ_t

Where$D^i = (x_i, y_i, L_i, \theta_i, d_i)$, representing x and y coordinate of the center, length, inclination and width of the block components. $H(x)$is the Heaviside function and it is used to calculate the sensitivity with respect to arbitrary geometry parameter a as follows:

$$\frac{\partial C}{\partial a} = -u^T(\frac{E}{4}(\sum_{e=1}^{NE}\sum_{i=1}^{4} q\big(H(\phi_i^e)\big)^{q-1}\frac{\partial H(\phi_i^e)}{\partial \alpha})K^s)u \tag{9}$$

The derivative of Heaviside function is calculated using Finite Difference Method in [14], [15] and the optimization problem is solved by the Method of Moving Asymptotes.

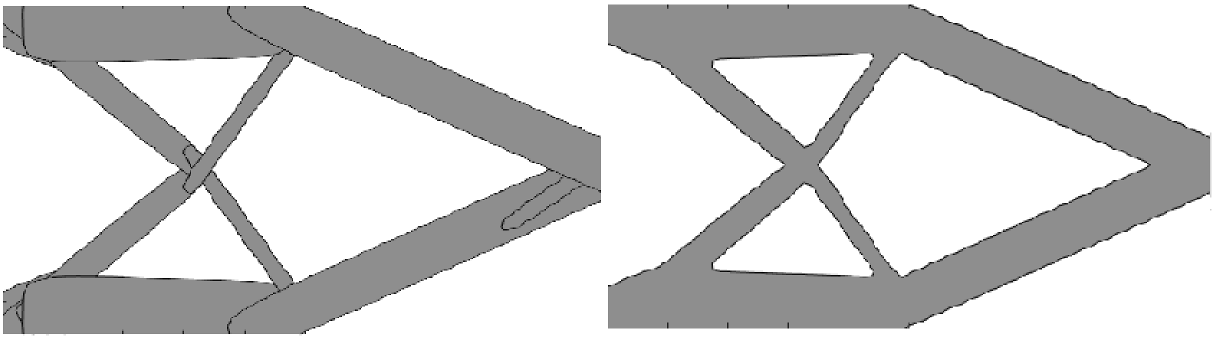

Figure 3 Optimal design obtained by MMC with and without the component contour

Figure 3 shows the obtained stucture by MMC approach. On the right hand side is the overall configuration while on the left the components forming the structure are shown. By applying MMC, a similar stucture is obtained as output by MMLS. There are two advantages of MMC. First, the width is fixed throughout each component, which is very important in terms of manufacturing of FRP composites. Second, there is an explicit mathematical expression for every component. However, MMC does have three shortcomings. First, current MMC performs only single material optimization therefore additional operations are needed to achieve a multi-material optimum. Second, due to the geometry features of the building components, it is difficult to obtain a complicated structure by applying MMC solely. Third, the optimum lacks of details especially at joints. In this particular design problem, uniform beams are made from composites where realisticaly are not simply joined together without changing the shape and property at these points. Although MMC outputs a promising overall structure, with controlled geometry features, it needs further developments to achieve an optimal composite-metal topology.

2.4 MMC+Level Set (LS)

2.4.1 Overlap refinement using Volume Threshold

To get an 'efficient' composite-metal hybrid structure topology, in this paper an optimization routine based on existing MMC and MMLS is introduced. In this routine, an overall structural frame is obtained by MMC, as shown in Figure 3. Then the volume of each candidate components is collected and listed in the volume array. A volume threshold is set to filter out the unrealistic regions i.e. overlapping joints. Figure 4 shows the difference in the removal filter by adjusting the volume threshold. The higher the threshold, the less the relatively unimportant components remains, which results in less noise in the coarse frame. At present work, the filtering scheme is simply based on the volume. Future research can be done on the improvements of the filter, taking the position of the components into account, for example.

With further modification including the addition extra material in internal holes inside closed regions, a refined structure is obtained as shown in Figure 5.

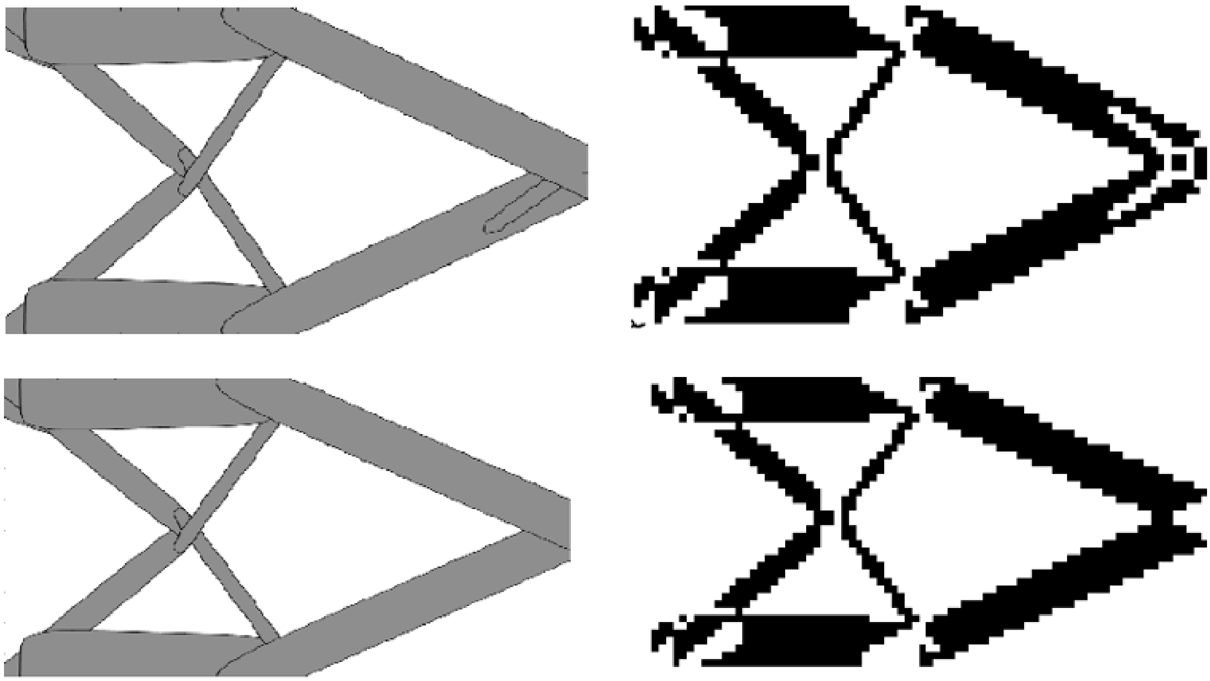

Figure 4 Filtered structure and its coarse frame with volume threshold=40 (upper) and 50 (lower)

Figure 5 Graph of refined frame

2.4.2 Refined structure + LS

Aluminum (shown in black in Figure 6) is then filled in the rest of the domain, followed by a single-material topology optimization using level set based method.

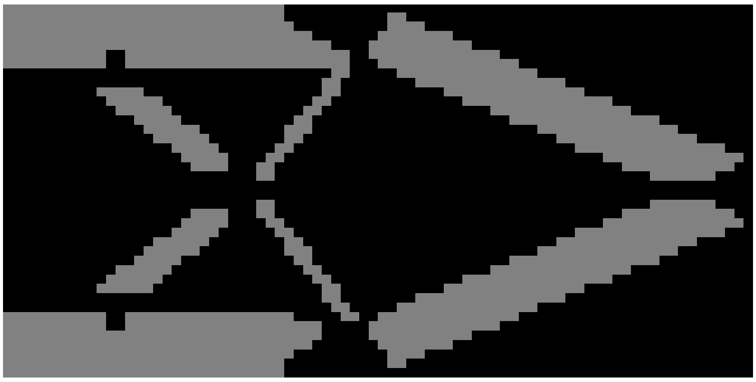

Figure 6 Aluminum occupies 67% of the design domain

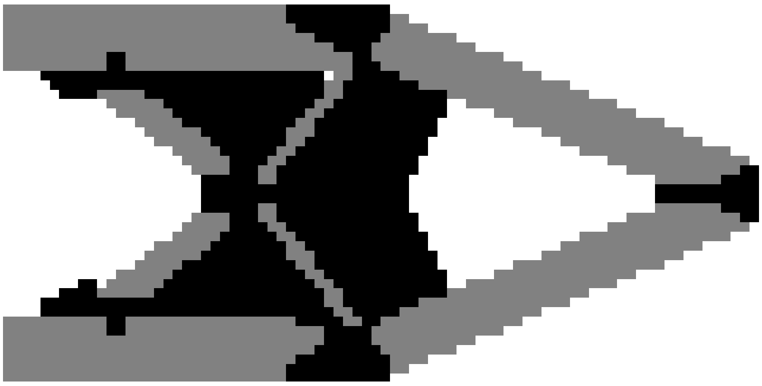

Figure 7 Aluminum occupies 25% of the design domain

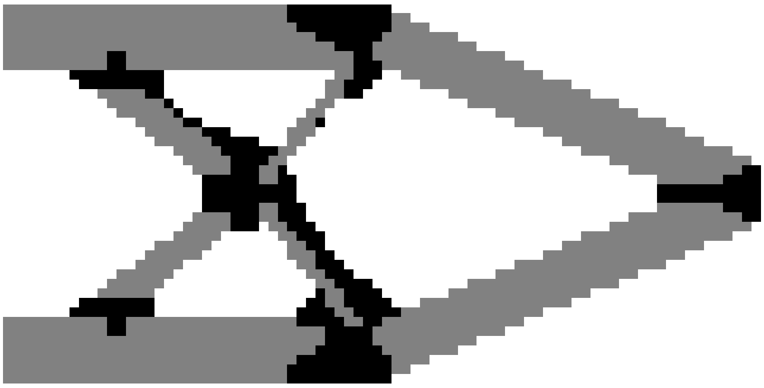

Figure 8 Aluminum occupies 10% of the design domain

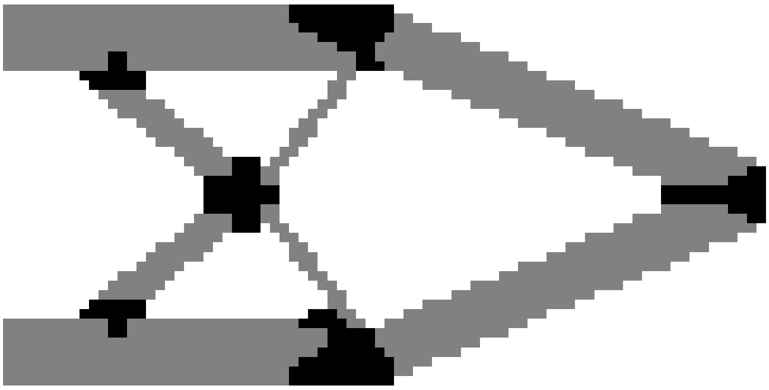

Figure 9 Aluminum occupies 7% of the design domain

Figure 6 to Figure 9 show the topology optimization process of the hybrid structure. It is a relatively simple implementation of level set based method. As the volume fraction of aluminum decreases, aluminum tends to accumulate in regions with the highest strain energy. Also, the complex geometries at the joints which are not easily achieved by using MMC solely are easily formed by level sets. As a result, the obtained structure has the following advantages: Firstly, the material ratio is still controllable in case the total material cost needs to be optimized against the compliance. Secondly, the geometry features are controllable by constraint the width function as a constant. In this way, the manufacturability of the hybrid structure is ensured and the cost to build this structure is minimized. Most importantly, this routine embedded some logic in the conventional topology optimization by distributing specific materials in specific regions.

3 CONCLUSIONS

In the present paper, an optimization routine for composite-metal aircraft structure based on the existing TO approaches (i.e. MMC and MMLS) is proposed. This routine mainly addresses two problems, the physical meaning of material distribution and the manufacturability of the structure. Instead of simply piling up multiple materials to satisfy the volume constraint, the proposed method distribute materials according to their features and usage. Also, the manufacturability of the structure is ensured by embedding geometry parameters into the design process. However, the proposed method does have its weakness on the identification of the joints. Future work will be focusing on the improvements on joints identification scheme and the expansion of this method from 2-dimensional to 3-dimensional.

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