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Proceeding Paper

# Optimisation of Fibre Reinforced Hybrid Composites Using Design of Experiments†

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**Abstract:** Fibre reinforced hybrid composites is made by reinforcing a matrix with two or more types of fibres. For layered composite materials, it is shown from previous research that the flexural strength can be improved by hybridising carbon and glass fibres. The strain-to-failure is improved by including higher strain-to-failure glass fibre plies. The existence of hybrid effect can be potentially useful for achieving a balanced cost and weight optimal composite material. The flexural properties of hybrid composites are affected by many parameters including fibre volume fraction, orientation of fibre, and degree of hybridisation or hybrid ratio. Finding the optimal configuration given the required flexural strength and/or flexural stiffness is not a trivial task. Traditional optimisation methods are usually based on non-dominated sorting GA-II (NSGA-II), and are very time-consuming so infeasible for practical applications. In this paper, an optimisation method based on Design of Experiments (DoE) is presented. Response surfaces are constructed using Central Composite Design (CCD). The optimal design can be conveniently derived using these response surfaces.

**Keywords:** Composites; Hybrid; Flexural; Design of Experiments (DoE)

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## 1. Introduction

Fibre reinforced hybrid composites is made by reinforcing a matrix with two or more types of fibres. A common type of hybrid composites is carbon and glass fibre reinforced hybrid composite. It is shown from previous research [1] that the flexural strength can be improved by hybridising carbon and glass fibres. The strain-to-failure is improved by including higher strain-to-failure glass fibre plies [2]. The existence of hybrid effect can be potentially useful for achieving a balanced cost and weight optimal composite material.

The properties of composites can be obtained analytically by Classical Lamination Theory (CLT) or numerically by Finite Element Analysis (FEA). In our previous research [3], the flexural properties of composites were obtained by the analytical approach based on simple CLT. In addition to CLT, the flexural properties of composites can also be obtained by the numerical approach based on FEA [4]. A recent study has shown that CLT underestimates the flexural strength [5].

In the design process of a layered composite, the fibre type, fibre orientation and fibre volume fraction of each ply need to be carefully selected to meet the design requirements. Because of the number of design variables, optimisation of composites is not a trivial task. Extensive research has been done on the optimisation of composites [6-8]. Two important design objectives are weight and cost minimisation. These two requirements are usually conflicting and thus trade-off needs to be made. An optimisation problem to minimise the cost and weight of composites is called a multi-objective optimisation problem.

Evolutionary algorithms, e.g., genetic algorithm (GA), are often used for the multi-objective optimisation of composites. A modified version of the NSGA, known as NSGA-II, is one of the most popular MOEAs due to its simplicity and efficiency [9]. NSGA-II has been used in our previous research to minimise the cost and weight of unidirectional and multidirectional hybrid composites [3]. It is shown that the positive hybrid effects help to reduce the cost and weight of the composite.

Since CLT underestimates the flexural strength, for better accuracy, FEA-based simulation was adopted in this study to find the flexural properties of hybrid composites. When NSGA-II and FEA are coupled, because for each run in NSGA-II, the FEA model needs to be updated, the multi-objective optimisation is preventively time-consuming and infeasible for practical use [5].

In this paper, an optimisation method based on Design of Experiments (DoE) is presented. With the selected design parameters, a Central Composite Design (CCD) is formulated. The output is generated using FEA model, and the response surfaces are constructed. The Response Surface Optimisation (RSO) [10] is done to minimise the total cost and total weight. Since only a limited number of FEA is required, the response surfaces can be obtained efficiently, and the optimal design can be conveniently derived using these response surfaces.

## 2. Methodology

### *2.1. Material Properties*

In this study, the fibre types being included in optimisation are high strength carbon fibre and E glass fibre. An epoxy was chosen to be the matrix. For each ply, based on the constituent properties and its fibre volume fraction, the ply properties, including the longitudinal modulus $E_{11}$, the transverse moduli $E_{22}$ and $E_{33}$, and the shear moduli $G_{12}$, $G_{13}$ and $G_{23}$, are derived by Hashin's model [11]. The strength components of composites were derived, and stress-based failure criteria were employed. The failure criterion is defined to be the ratio of the maximum stress and strength.

The weight of a composite material can be characterised by its density. The density of the hybrid composite reinforced by carbon and glass fibres, $\rho_c$, can be derived based on RoM as follows:

$$\rho_c = \rho_{fc}V_{fc} + \rho_{fg}V_{fg} + \rho_m V_m \tag{1}$$

where $\rho_{fc}$, $\rho_{fg}$ and $\rho_m$ are the densities of carbon fibre, glass fibre and the matrix, respectively, and $V_{fc}$, $V_{fg}$ and $V_m$ are the volume fractions of carbon fibre, glass fibre and the matrix, respectively.

The material cost of the hybrid composite, $C_c$, is given by

$$C_c = C_{fc}V_{fc} + C_{fg}V_{fg} + C_m V_m \tag{2}$$

where $C_{fc}$, $C_{fg}$ and $C_m$ are the costs of carbon fibre, glass fibre and the matrix, respectively.

### *2.2. FEA-Based Model*

The hybrid composite in this study consists of eight plies and the thickness of each ply is 0.25 mm. The total thickness is 2 mm, the width is 10 mm, and the length is 100 mm. three-point bend test in accordance with ASTM D7264 [12] is simulated to obtain the flexural properties. The details of the FEA-based simulation can be found in [5].

### *2.3. Design of Experiments*

Central Composite Design (CCD) is chosen in this study. For the purpose of limiting the number of required design points, the parameters chosen to be included in the DoE are the ply materials of layers 1, 2, 7, and 8, and the fibre volume fractions of carbon/epoxy and glass/epoxy layers. For both fibre volume fractions, the lower and upper bounds are 0.3 and 0.65, respectively. Response surfaces can then be constructed. As an example, the response surface for layup [$0_{2G}/0_{6C}$] is shown in Fig. 1. In Fig. 1, the contour lines show the flexural strengths in MPa. It is seen the flexural strength in general increases with both fibre volume fractions.

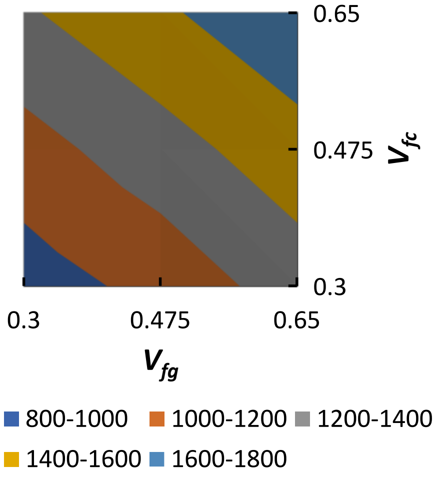

**Figure 1.** Response surface of flexural strength for layup [$0_{2G}/0_{6C}$].

In this study, three minimum flexural strengths: 1000 MPa, 1300 MPa, and 1600 MPa, are chosen. Given the required minimum flexural strength, the RSO is done to minimise the total cost and total weight.

## 3. Results and Discussion

The Pareto fronts of the unidirectional carbon and E glass fibre reinforced hybrid composite from the RSO are shown in Fig. 2. The widest ranges of areal weight and areal cost are shown when the required minimum flexural strength is 1000 MPa. The ranges of areal weight and areal cost slightly decrease when the required minimum flexural strength is 1300 MPa. The ranges of areal weight and areal cost become quite narrow when the required minimum flexural strength is 1600 MPa. Compared to 1000 MPa and 1300 MPa, significantly higher cost is when for 1600 MPa, indicating the application of more carbon fibre.

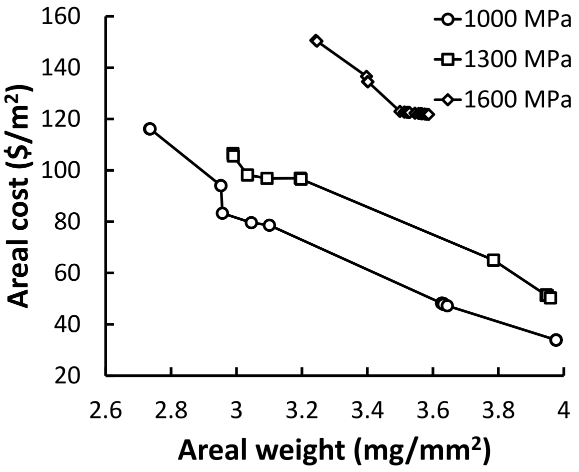

**Figure 2.** Pareto fronts of unidirectional hybrid composites reinforced by carbon and E glass fibres.

When the candidates are examined, it is shown many candidates have glass/epoxy for layers 7 and 8, which are on the compressive face. This further confirms that positive hybrid effects help to improve the flexural strength.

## 4. Conclusions

In this paper, an optimisation study on hybrid composites under flexural loading is presented in this paper. Response surfaces are constructed using CCD. Given the required minimum flexural strength, multi-objective optimisation with minimum cost and weight as the objective functions is done with the aid of the response surfaces, and a Pareto front of optimal candidates are found. The presented research is potentially useful for the design of lightweight structures. For complex composite components, FEA can be applied to simulate the performance under given loadings. Optimisation can be efficiently done with the aid of RSO. The time-consuming process of NSGA-II can be avoided.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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