OPTIMISATION OF HYBRID COMPOSITE REINFORCED CARBON AND GLASS USING AHP METHOD

Nur Aizatul 'Ain Md Zahir[1,3], Ahmad Fuad Ab Ghani[2,3], Mohd Ahadlin Mohd Daud[1,3*], Sivakumar Dharmalingam[1,3] & Ridzuan Mansur[1,3]

[1]Fakulti Kejuruteraan Mekanikal (FKM)
[2]Fakulti Kejuruteraan Teknologi Mekanikal dan Pembuatan (FTKMP)
[3]Centre for Advanced Research on Energy (CARe)
Universiti Teknikal Malaysia Melaka (UTeM), Malaysia

[*]Email: ahadlin@utem.edu.my

ABSTRACT

Aiming for the selection of carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) hybrid composite with the best combination of strength, weight and cost, the analytical hierarchy process (AHP) method was applied. Ten composite configurations were arranged with different design criteria such as flexural strength, flexural modulus, strain to failure, density and cost and were then ranked by AHP method. AHP results revealed that C1with relative PV of 23.24% was the preferred hybrid composite for CFRP/GFRP design configuration. It was also concluded that the flexural strength of the design criteria was the most significant property which may affect the mechanical properties of the hybrid composite.

Keywords: *Hybrid composite; carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP); optimisation; analytical hierarchy process (AHP).*

1. INTRODUCTION

In engineering field, design techniques and analysis often become complicated when it comes to design improvement and optimisation (Ab Ghani & Mahmud, 2017). For example, in order to improve the mechanical properties of composite sandwich structure, the design variables that should be taken into considerations include ply orientations, face sheets stacking sequence, and thickness of the core. Thus, the analysis and design of the sandwich structure is far more complicated than the traditional sandwich structure with isotropic material properties. To cope with these complexities, the techniques and methodologies of design optimisation should be developed.

The optimisation of composite laminates has been initiated by the American aerospace industry with fibre volume and orientation angles as design variables. This method of optimisation is also restricted to simple laminates design and load cases only (Schläpfer, 2013). The optimisation could unlock the next level of hybrid composite capabilities because the large number of design variables could be provided. This will bring a great potential for tailoring the composite laminates properties to meet certain requirements but it will implies a complex engineering problem. Thus a better solution in optimisation that requires less time can be found by using computational optimisation method (Schläpfer, 2013).

A few modern approaches for the design of composite structures have been studied by Axinte *et al*. (2013) which covered genetic algorithm (GA), simulated annealing method (SAM), particle swarm optimisation (PSO) and ant colony optimisation (ACO). Another powerful tool that has been used for optimisation of composite material is analytical hierarchy process (AHP) (Mansor *et al*., 2014;

Zafarani *et al*., 2014). Baragetti (2014) stated that AHP is capable in formulating and handling a complex problem hierarchally.

Certain constrains can be found in a number of research dealing with optimising the hybrid composite materials Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP). One of the most studied industries for composite application is the defence industry where numerous researchers attempt to improve the existing part in the defence industry such as body armour and ballistic composite components (Supian *et al.,* 2018). In addition, Sapuan *et al*. (2011) systematically organised the database of material selection for natural fibres that can be used in the application of AHP for development of automotive dashboard panel. Throughout the study, the kenaf 60% + polypropylene (PP) shows a domination of three out of four simulated scenarios in AHP. The sensitivity analysis that have been conducted to verify the results have also shown similar results thus the AHP approach was proven as a useful method to solve decision problem by providing clear criteria and priority during material selection process. The reduction of weight and manufacturing cost of automotive armrest is achievable by replacing the steel frame with Vinylester resin when the AHP approach was implemented. AHP was used to evaluate the data and select the best alternative based on the criteria to decide the thermoset matrix for natural fibre composites automotive armrest (Rosli *et al*., 2017).

In this study, the process and methodologies for optimisation process were developed and briefly discussed from the design configurations of composite material until the selection of the best composite design configurations. The finite element analysis was implemented, and the steps involved were explained in detail including flexural analysis modelling step and failure criteria. In addition, this section explains the optimisation method by using AHP approach to determine the optimised design configurations of composite material.

2. METHODOLOGY

2.1 Material Properties

The composite laminates structure consisted of CFRP and GFRP layup, represented by orange region – CFRP and blue region – GFRP in Figure 1. The mechanical properties of CFRP and GFRP are tabulated in Table 1. There are ten different arrangement of composite structure with the purpose to investigate the behaviour under the same condition. All cases consist of unidirectional fibre direction and symmetry arrangement as shown in Figure 1.

Table 1: Material database for CFRP and GFRP.

Mechanical Properties	CFRP	GFRP
Longitudinal elastic modulus, E1 (GPa)	128.80	45.20
Transverse elastic modulus, E2 (GPa)	9.30	14.10
Major Poisson's ratio, V12	0.34	0.29
Shear Modulus, G12 (GPa)	3.37	6.30
Thickness per layer (mm)	0.20	0.187

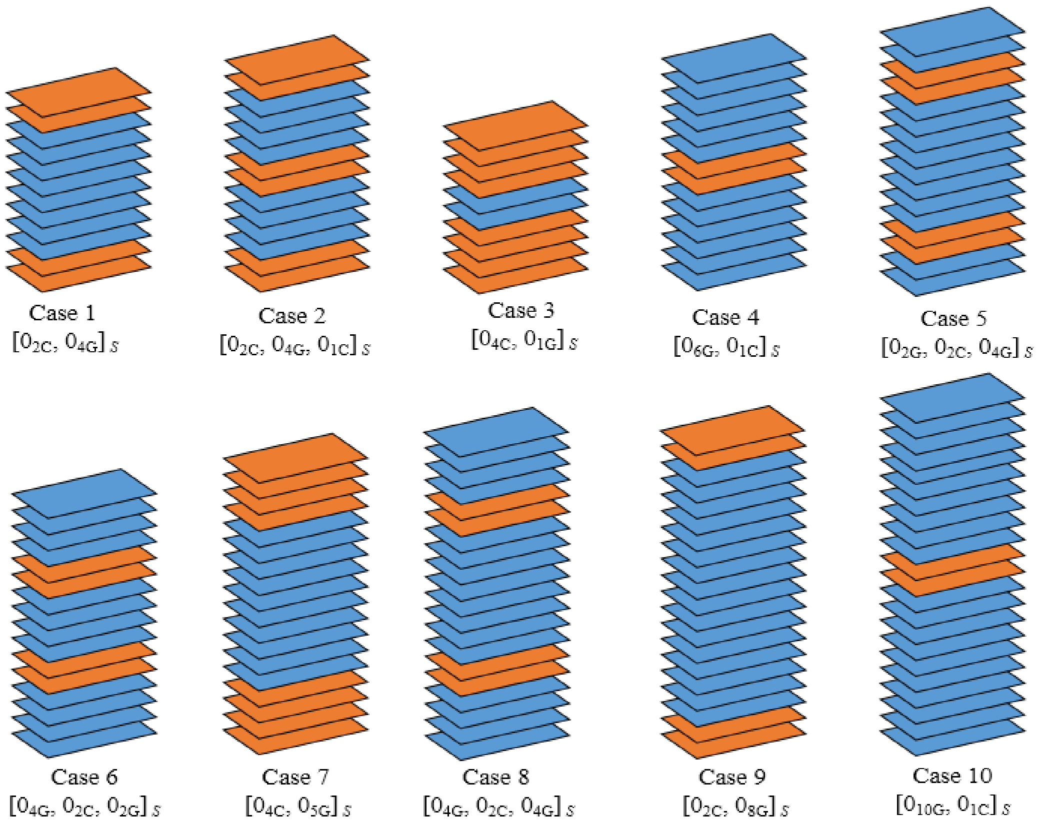


Figure 1: Ten composite laminates configurations.

The cost for each composite material CFRP and GFRP was based on the current price from Rockwest Composite (TORAY T700S Data Sheet, 2018). The cost of the hybrid composite material is calculated based on its weight and the price of material per unit weight. The price is then calculated according to the dimension of the sample in this study which is 40 mm × 15 mm.

2.2 Finite Element Analysis (FEA)

In FEA simulations, the composite structure was divided into finite number of elements. The stress and strain results under flexural loading were obtained by FEA using ANSYS APDL. Composite specimen was modelled with dimension of 40 mm in length, 15 mm in width and specific thickness according to each case. An example of hybrid composite CFRP/GFRP finite element model under the three point bending in ANSYS APDL is shown in Figure 2.

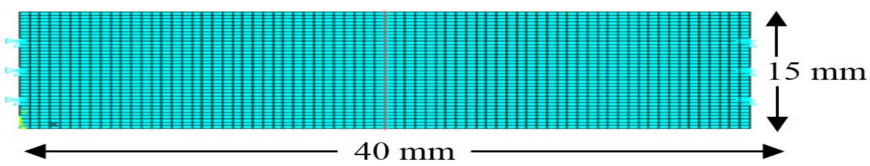


Figure 2: Composite model in ANSYS APDL.

In order to replicate three-point-bending test in the experiment, the model was mapped mesh at the area with quad element and refined at each node. The element type is SHELL181. Distributed load with sinusoidal distribution was applied which include downward distributed load (*P*) in the load point, and half of an upward distributed load (*P/2)* at the left and right ends of bottom surface. The two central points at each end of laminate (*z=h/2*) were restrained as *UX=UY=UZ=0* to eliminate the DOFs. Load was applied gradually along the middle nodes as line load (Force/Width) until the whole layers failed by using the concept of Last Ply Failure (LPF). Failure criteria are presented using the notion of failure index, $I_F$in ANSYS APDL where failure is predicted if the I_F> 0 for all layers in the composite laminates. The flexural strength (σ_F), strain to failure (ε_F) and flexural modulus (E_F) are determined given by Equation 3.1, Equation 3.2 and Equation 3.3 respectively (Standard ASTM D790, 1997):

$$\sigma_F = \frac{3F_{\max}L}{2bh^2} \tag{1}$$

$$\varepsilon_F = \frac{6Dh}{L^2} \tag{2}$$

$$E_F = \frac{L^3 m}{4bh^3} \tag{3}$$

where *L, b* and *h* are the span length, width and thickness of the specimen, *m* is the slope of the tangent to the straight line of load vs. deflection curve, *D* is the maximum deflection before failure, and $F_{max}$is the maximum load before specimen failure.

2.3 Analytical Hierarchy Process (AHP)

AHP is one of the decision-making tools developed by Prof. Thomas L. Saaty in 1980. AHP is implemented when there are multiple and conflicting criteria present, as well as when both of the qualitative and quantitative aspects of a decision need to be considered. It is an effective choice in dealing with a complex decision making since it reduces complex decision to a series of pair-wise comparison. AHP works by considering a set of evaluation criteria along with the alternatives scenarios to decide which decisions is the best.

For decision making process, a weight for each evaluation criterion and scenario is generated following the information provided and the ranking of the scenarios will be determined. There are three fundamental steps in AHP, (i) defining a multi-criteria problem hierarchically, (ii) assigning relative priorities to the various elements using pair-wise comparison techniques and (iii) integrating these priorities to converge at an overall evaluation of decision alternatives. The concept of relative importance by Saaty (1980) in Table 2 is used when assigning weights to the alternatives as well as criteria for constructing the decision matrix and pair-wise comparison matrices.

In AHP, the decision matrix and pair-wise comparison matrices are in the form of square matrices. Eigen values and Eigen vectors are used to check the consistency of the judgment values assigned to the decision alternatives and criteria and if required, the decision-maker revises and modifies judgment values. Before evaluation process takes place, the goal in this study is to analyse and evaluate different design configurations of composite laminates to obtain the most optimum design.

Table 2: Intensity of relative importance.

Intensity of relative importance	Definition
1	Equally important
3	Moderately preferred
5	Essentially preferred
7	Very strongly preferred
9	Extremely preferred
2,4,6,8	Intermediate importance between two adjacent judgments

In this study the selection of the best design configurations of the composite laminates CFRP/GFRP depends upon six evaluation criteria. The optimisation of hybrid composite can be measured in terms of flexural strength, flexural modulus, strain to failure, density and cost. All the evaluation criteria were selected based on the most studied criteria for hybrid composite material based on the literature study. Table 3 displays the identified criteria with their operational definitions.

Table 3: Selected criteria for optimisation of hybrid composites.

No.	Criteria and Code	Operational Definition
1.	Flexural Strength, F_1	Highest stress experienced within the material at its moment of yield.
2.	Flexural Modulus, F_2	Tendency for a material to resist bending.
3.	Strain to Failure, F_3	The maximum elongation of material, i.e. at break.
4.	Density, F_4	Ratio of weight of the composite material to the volume of the composite material
5.	Cost, F_5	Composite materials costs

Ten composite plate configurations (Figure 1) are considered and coded as C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8, C_9 and C_{10}. It is presumed that the behaviour/performance of these ten alternatives (composite configurations) with respect to each of the six criteria is known. The list of the set of design configurations is listed in Table 4.

Next, the pair-wise comparison matrices were developed for each design criterion in Figure 3 to identify the ranking of importance of design criteria. Pair-wise comparison begins with comparing the relative importance of two design criteria by using relative pair-wise comparison by AHP template from SCBUK. The decision matrix was developed by assigning weights to each design criteria based on the relative importance of its contribution according to the nine-point scale. The judgments or assigned values are based on the experience, knowledge, through journals and handbooks.

For each of the pair-wise comparison matrices, the normalised score (NS) is determined to calculate the priority vectors (PV) for decision matrix. The sum of each of the column is multiplied by the corresponding PV value as in Figure 3. Calculation of the sum of these products, i.e., the principal eigen value (λ_{max}) is done in order to check the consistency index and consistency ratio. The consistency is less than 10% thus the judgment is acceptable.

Table 4: List of the set of design configurations (C1 to C10).

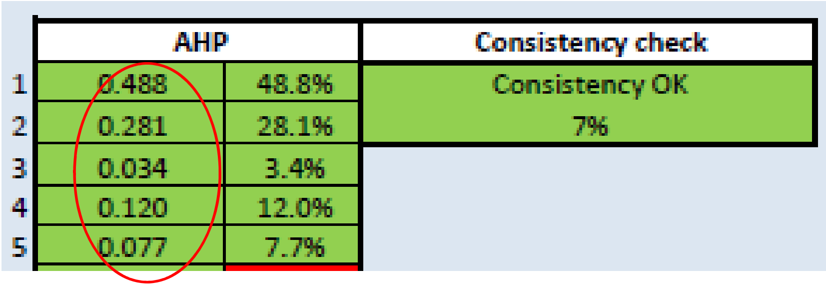
Case	Laminate Configuration	Symbol
Case 1	$[C_2/G_4]s$	C_1
Case 2	$[C_2/G_4/C_1]s$	C_2
Case 3	$[C_4/G_1]s$	C_3
Case 4	$[G_6/C_1]s$	C_4
Case 5	$[G_2/C_2/G_4]s$	C_5
Case 6	$[G_4/C_2/G_2]s$	C_6
Case 7	$[C_4/G_5]s$	C_7
Case 8	$[G_4/C_2/G_4]s$	C_8
Case 9	$[C_2/G_8]s$	C_9
Case 10	$[G_{10}/C_1]s$	C_{10}

Pairwise Comparison Matrix	Design criteria				
	Flexural Strength	Flexural Modulus	Strain to failure	Density	Cost
Flexural Strength	1	2	9	6	7
Flexural Modulus	1/2	1	8	2	6
Strain to failure	1/9	1/8	1	1/4	1/4
Density	1/6	1/2	4	1	2
Cost	1/7	1/6	4	1/2	1

Figure 3: Pair-wise comparison matrix for design criteria.

A consistency indicates how a given matrix compares to a purely random matrix in terms of their consistency indices, and acceptable consistency is when Consistency is ≤ 10%. Thus, larger consistency value requires the judgment to be reiterated until Consistency of < 10% is reached (Mansor *et al*., 2014). Priority vectors (PV) indicates how important a criterion is among the other criteria. For instance, the flexural strength (F1) contributes the highest to the goal with priority vector of 48.8% while the strain to failure (F3) contribute the lowest with the priority vector of 3.4% only.

This means that flexural strength is the most important consideration with respect to the hybrid composite laminates criterion to the other criteria. The ranking of the design criteria decisions are shown in Figure 4. It shows that the most important criteria is flexural strength, followed by flexural modulus, density, cost and strain to failure.



	AHP		Consistency check
1	0.488	48.8%	Consistency OK
2	0.281	28.1%	7%
3	0.034	3.4%	
4	0.120	12.0%	
5	0.077	7.7%	

Figure 4: Priority vector (PV) for criterion decision matrix.

The criteria that influence the selection process factor of design configurations were then translated into the hierarchy structure in Figure 5. The pair-wise comparison for design configurations for each design criteria is performed. Based on tabulated data in Table 5, the weights to each of the alternatives (design configuration) were assigned, based on its relative importance, according to nine-point scale.

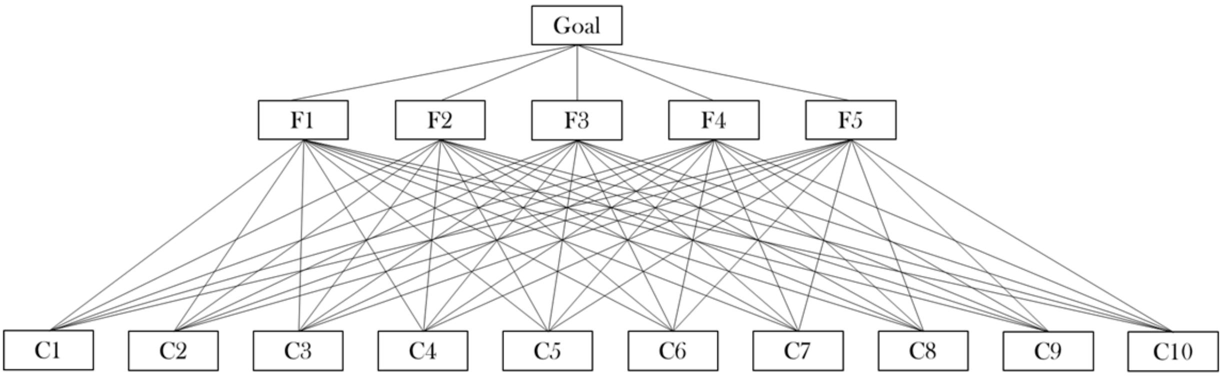


Figure 5: Hierarchy structure of design criteria and design configurations.

Table 5: Criteria values for AHP.

Case	Flexural Strength (MPa)	Flexural Modulus (GPa)	Strain to failure	Density (kg/m^3)	Cost ($)
1	1714.8442	73.2451	0.0234	2.9036	0.2194
2	1447.3580	68.3092	0.0212	2.7201	0.2631
3	1611.6300	90.4862	0.0178	2.0263	0.2079
4	1384.6897	39.4143	0.0351	3.2779	0.2416
5	1705.1704	51.3319	0.0332	3.0661	0.2853
6	1683.5860	43.3880	0.0388	3.0661	0.2853
7	1162.7038	66.4912	0.0175	2.6897	0.3398
8	1641.2523	41.3398	0.0397	3.1646	0.3512
9	1349.1650	54.0735	0.0250	3.1646	0.3512
10	1225.2328	33.9737	0.0361	3.3816	0.3735

3. RESULTS & DISCUSSION

The ten design configurations of composite laminates CFRP/GFRP were evaluated in order to determine the most optimum composite laminates design concept which has high flexural properties, and at the same time possess low cost and low densities. In general, AHP composed of three basic steps; decomposition, comparative judgment and synthesis. The pair-wise comparison that has been made to the design configurations for each design criteria are shown in Figure 6 – Figure 10.

Flexural Strength

Pairwise Comparison Matrix

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Case 1	1	6	5	7	2	3	9	4	8	9
Case 2	1/6	1	1/2	2	1/4	1/3	4	1/3	3	3
Case 3	1/5	2	1	2	1/3	1/3	5	1/2	3	4
Case 4	1/7	1/2	1/2	1	1/5	1/4	3	1/3	2	2
Case 5	1/2	4	3	5	1	2	8	2	6	7
Case 6	1/3	3	3	4	1/2	1	7	2	5	6
Case 7	1/9	1/4	1/5	1/3	1/8	1/7	1	1/6	1/3	1/2
Case 8	1/4	3	2	3	1/2	1/2	6	1	4	5
Case 9	1/8	1/3	1/3	1/2	1/6	1/5	3	1/4	1	2
Case 10	1/9	1/3	1/4	1/2	1/7	1/6	2	1/5	1/2	1

Figure 6: Pair-wise comparison of design configurations with flexural strength.

Flexural Modulus

Pairwise Comparison Matrix

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Case 1	1	2	1/2	7	4	5	2	6	3	8
Case 2	1/2	1	1/2	6	3	4	2	5	2	7
Case 3	2	2	1	8	5	6	3	7	4	9
Case 4	1/7	1/6	1/8	1	1/3	1/2	1/5	1/2	1/4	2
Case 5	1/4	1/3	1/5	3	1	2	1/2	2	1/2	4
Case 6	1/5	1/4	1/6	2	1/2	1	1/3	2	1/2	3
Case 7	1/2	1/2	1/3	5	2	3	1	4	2	6
Case 8	1/6	1/5	1/7	2	1/2	1/2	1/4	1	1/3	2
Case 9	1/3	1/2	1/4	4	2	2	1/2	3	1	5
Case 10	1/8	1/7	1/9	1/2	1/4	1/3	1/6	1/2	1/5	1

Figure 7: Pair-wise comparison of design configurations with flexural modulus.

Strain to Failure

Pairwise Comparison Matrix

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Case 1	1	2	2	1/3	1/2	1/5	3	1/6	1/2	1/4
Case 2	1/2	1	2	1/4	1/3	1/6	2	1/7	1/2	1/5
Case 3	1/2	1/2	1	1/5	1/4	1/7	2	1/8	1/3	1/6
Case 4	3	4	5	1	2	1/2	6	1/3	2	1/2
Case 5	2	3	4	1/2	1	1/3	5	1/4	2	1/2
Case 6	5	6	7	2	3	1	8	1/2	4	2
Case 7	1/3	1/2	1/2	1/6	1/5	1/8	1	1/9	1/4	1/6
Case 8	6	7	8	3	4	2	9	1	5	2
Case 9	2	2	3	1/2	1/2	1/4	4	1/5	1	1/3
Case 10	4	5	6	2	2	1/2	6	1/2	3	1

Figure 8: Pair-wise comparison of design configurations with strain to failure.

Density

Pairwise Comparison Matrix

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Case 1	1	1/2	1/3	3	2	2	1/2	2	2	4
Case 2	2	1	1/2	4	2	2	1/2	3	3	5
Case 3	3	2	1	6	4	5	2	5	5	7
Case 4	1/3	1/4	1/6	1	1/2	1/2	1/5	1/2	1/2	2
Case 5	1/2	1/2	1/4	2	1	1	1/3	2	2	3
Case 6	1/2	1/2	1/5	2	1	1	1/3	2	2	3
Case 7	2	2	1/2	5	3	3	1	4	4	6
Case 8	1/2	1/3	1/5	2	1/2	1/2	1/4	1	1	2
Case 9	1/2	1/3	1/5	2	1/2	1/2	1/4	1	1	2
Case 10	1/4	1/5	1/7	1/2	1/3	1/3	1/6	1/2	1/2	1

Figure 9: Pair-wise comparison of design configurations with density.

Cost

Pairwise Comparison Matrix

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
Case 1	1	2	1/2	2	3	3	4	5	5	6
Case 2	1/2	1	1/3	1/2	2	2	2	3	3	4
Case 3	2	3	1	2	4	4	5	6	6	7
Case 4	1/2	2	1/2	1	2	2	3	4	4	5
Case 5	1/3	1/2	1/4	1/2	1	1	2	2	2	3
Case 6	1/3	1/2	1/4	1/2	1	1	2	2	2	3
Case 7	1/4	1/2	1/5	1/3	1/2	1/2	1	2	2	2
Case 8	1/5	1/3	1/6	1/4	1/2	1/2	1/2	1	1	2
Case 9	1/5	1/3	1/6	1/4	1/2	1/2	1/2	1	1	2
Case 10	1/6	1/4	1/7	1/5	1/3	1/3	1/2	1/2	1/2	1

Figure 10: Pair-wise comparison of design configurations with cost.

The composite priority (CP) of the design configurations were then determined by multiplying the PV values for a particular criterion with the corresponding PV value of that criterion, and adding up these products. Design configurations that have the highest CP showed the design configuration that is best in terms of evaluated criteria. The result for CP for all design configurations is shown in Table 6.

Based on the % of CP, the ranking of the design configurations decisions are determined as shown in Figure 11. Among all design configurations, C1 is the only one that has the % CP of above 20% which is the largest one considering there is ten competitive configurations. Between the composites configurations with the same % of CFRP and GFRP, same manufacturing cost, and same density (C5 & C6; C8 & C9), the controlling parameter is the flexural strength, flexural modulus and strain to failure. It showed that the design concept Case 1 (C_1) with a % CP of 0.2325 (23.25%) is the first choice, the second choice is the design concept Case 3 (C_3) with a %CP of 0.1662 (116.62%) and third choice is the design concept Case 5 (C_5) with a % CP of 0.1274 (12.74%).

Table 6: Composite Priorities.

	F_1 0.488	F_2 0.281	F_3 0.034	F_4 0.12	F_5 0.077	Total	% CP
Case 1	0.302	0.201	0.044	0.102	0.193	0.232454	23.2454
Case 2	0.059	0.153	0.033	0.139	0.106	0.097749	9.7749
Case 3	0.076	0.27	0.025	0.267	0.264	0.166176	16.6176
Case 4	0.042	0.025	0.113	0.035	0.142	0.046497	4.6497
Case 5	0.191	0.061	0.083	0.072	0.072	0.127355	12.7355
Case 6	0.147	0.044	0.201	0.071	0.072	0.104998	10.4998
Case 7	0.018	0.113	0.019	0.19	0.052	0.067987	6.7987
Case 8	0.11	0.033	0.27	0.048	0.037	0.080742	8.0742
Case 9	0.032	0.083	0.061	0.048	0.037	0.049622	4.9622
Case 10	0.024	0.019	0.151	0.026	0.026	0.027307	2.7307

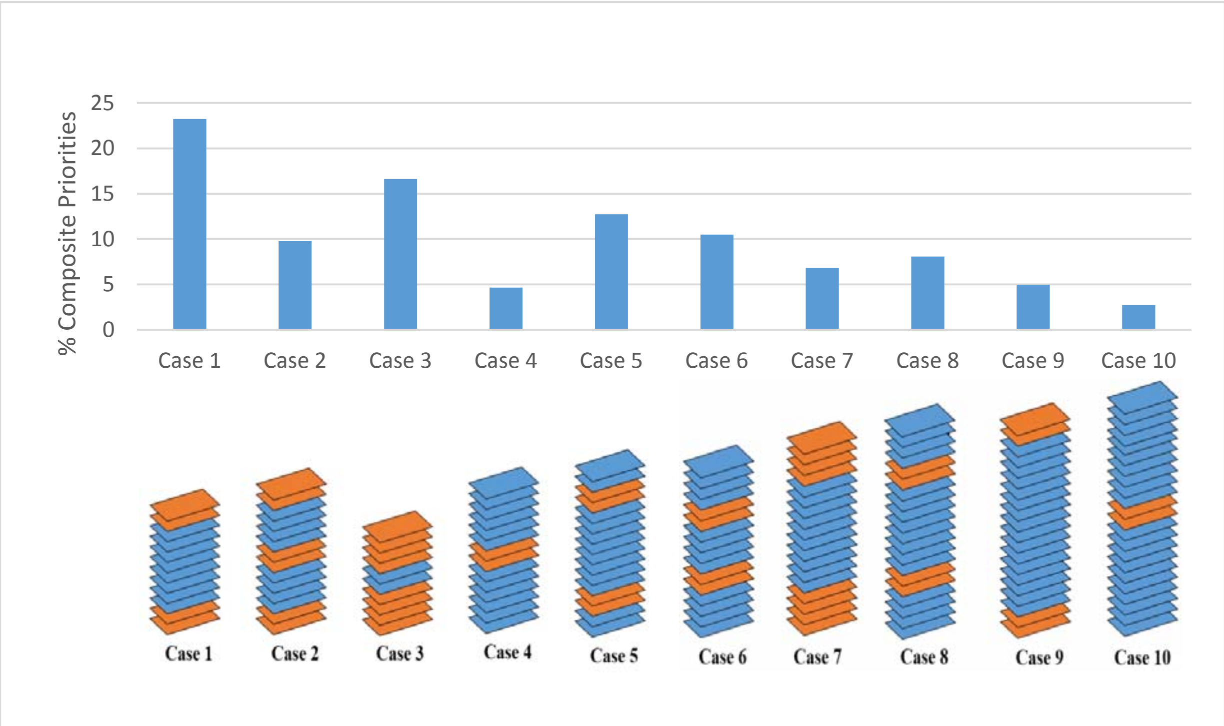


Figure 11: Ranking for design configurations.

The design configurations were found to have great influences on flexural properties of CFRP/GFRP hybrid composite. From Table 6, even though Case 1 has dominated only one out of the five evaluated criteria, however, Case 1 showed the highest global priorities followed by Case 3 and Case 5. The stacking sequence of composite laminates like Case 1 with CFRP plies placed at the outer layer of hybrid composite laminates could promote to the higher flexural strength that can withstand higher stress experienced within the composite laminates at its moment of yield. Besides that, by altering the stacking sequences of CFRP/GFRP hybrid composite, the lesser cost with lighter weight of composite laminates can be achieved. This can be shown with the comparison between Case 1 and Case 5. Case 1 possess a lighter weight and cost less than Case 5 with higher flexural properties which proved that the stacking sequence like Case 1 could promote more advantages compared to stacking sequence like Case 5.

Thus, it can be concluded that Case 1 is the best hybrid composite design configuration to be considered for the hybrid composite laminates formulation that satisfy all the required design specification for the intended application, which has the highest flexural properties while maintaining low cost and density. Similarly, the potential of configuration of Case 1 as the best design of composite laminates was also reported by Subagia *et al*. (2014) through the case study on effect of stacking sequence on flexural properties by hybrid composites reinforced carbon and basalt fibres. Their findings revealed that the interply hybrid composite with carbon fibre at the compressive and tension sides exhibited higher flexural strength and modulus than when basalt fabric was placed at the compressive side (Subagia *et al*., 2014).

4. CONCLUSION

The aim of this work is to select the optimal composite configurations that have the best combination of strength, weight and cost which is significant in structural applications in defence, automotive and aerospace industries. Analytic Hierarchy Process (AHP) was selected to be used as the multi-criteria decision making method. Ten design configurations of composites laminates were evaluated with the same design criteria which are flexural strength, flexural modulus, strain to failure, density and cost. Findings from AHP method showed that the choice of C1 with relative density of 23.24% is the preferred alternative. It also showed that flexural strength is the most significant design criteria which can affect the mechanical performances of the hybrid composites CFRP/GFRP due to its highest PV among the design criteria.

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