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Mechanical Properties Investigation of Composite Material Under Different Parameters Variations

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Abstract

The main objective of this research is to design and select a composite plate to be used in fabricating wing skins of light unman air vehicle (UAV). The mechanical properties, weight and cost are the basis criteria of this selection. The fiber volume fraction, fillers and type of fiber with three levels for each were considered to optimize the composite plate selection. Finite element method was used to investigate the stress distribution on the wing at cruise flight condition in addition to estimate the maximum stress. An experiments plan has been designed to get the data on the basis of Taguchi technique. The most effective parameters at the process to be find out by employing L_9 (3^3) orthogonal array, signal to noise ratio (S/N), main effect and analysis of variance (ANOVA). The results show that, the experimental and the predicted results are very close. It was found that the type of fiber is the most effective parameter on the plate selection, followed by filler content and then the fiber volume fraction. The best parameters combinations are ((E-glass woven roving + unidirectional carbon) fiber, 7.5% graphite filler and 30% fiber volume fraction). This combination provides good mechanical properties, high safety factor, acceptable cost, and offers weight savings on average by 40% percent as compared to aluminum alloy.

Keywords: *Mechanical properties, composite material, polyester, Taguchi technique.*

1. Introduction

In aero engineering applications, the strength to weight ratio and cost are the main factors influence the selection of material [1,2]. Composite materials are well known for their excellent combination of high structural stiffness and low weight [3,4]. Nowadays, the unman air vehicle (UAV) air frame use 70% composite materials. Whereas Boeing 787 use 50% composite materials in airframe and primary structure. This approach offers weight savings as compared with the conventional aluminum designs [5]. Composites material are composed of fibers and matrix. The main source of strength and reinforcement is fibers, while matrix make hold the fibers together in shape with the ability of stresses transfer between the fibers [6]. Matrix prevent formation of new surface flaws and abrasion by isolates the fibers from one another, able to deform under applied load and distributive stress [7]. Matrix holds fibers to maintain the required shape, but the fibers improves the matrix mechanical properties. Qahtan [8] investigated the physical and mechanical properties of composite materials polymer matrix with10% weight fraction. It is found that, the particle volume fraction effects on the properties of composite materials. Monika et al [9] had an experimental result presents that the failure of the tension specimens happens at the ends of straight gage section and the curved region begins transition. Whereas, Farag and Drai [10], demonstrated the mechanical and tribological behavior of glass-polyester composite system under the effect of graphite filler contents. It was found that with the graphite filler content increases up to 7.5%. The mechanical and tribological properties behavior improved.

Since, the mechanical properties, weight and cost are the main parameters that effect on the composite material selection. Taguchi technique and multiple regression models can be used to optimize these parameters. Drai et al [11] using Taguchi approach to investigate the mechanical and tribological behavior of glass-polyester composite material under different filler content. It is found that the additives parameter have the highest influence. Farag, Drai and Hussam [12], demonstrate the influence of graphite filler content on the sandwich panel glass-polyester deflection and deformation behavior subjected to low velocity impact by using Taguchi technique, and show that the mass has the main influence on the deflection, whereas the graphite filler is the dominate parameter influence on the deformation. Taguchi method is a powerful tool to design a high quality system and has been widely used in engineering analysis. Moreover, Taguchi method uses a special design of orthogonal array to demonstrate the entire parameters effects through a small number of experiments. Therefore, the time required for the experimental investigations is significantly reduced, and it is effective in the investigation of the multiple factors effect on the performance, as well as to study the influence of individual factors to determine which factor has more influence, which one less [13,14,15].

The main objective of this work is to design and select a composite plate to be used in fabricating wing skins of a light UAV. To investigate the influence of fiber volume fraction, filler and type of fibers on the composite plate selection parameters. An experiments plan has been designed to get the data on the basis of Taguchi technique in a controlled way.

2. Unman Air Vehicle Specifications

The UAV is a small short range tactical vehicle which is used for reconnaissance and surveillance missions. It operates in Iraq weather. designed with high aspect ratio wing, twin tail boom layout and a 3 hp power engine. Equipped with auto-pilot system and it can flight fully autonomous with the programmed flight track. The UAV specifications are shown in Table.1.

Table 1,
Specification of UAV.

Length	2 m
Wingspan	3 m
Airfoil	NACA 0012
Chord	0.35 m
Height	1.25 m
Maximum Speed	100 km/h
Cruise Speed	50-60 km/h
Ceiling	1000 m
Maximum Range	50 km
Max Takeoff Weight	30 kg
Navigation Mode	GPS

3. Experimental Test

Material: materials used are resin, fiber, filler and a hardener (Methyl Ethyl Kenton Peroxide) at room temperature. Resin is unsaturated polyester (UP). Fibers are; E-glass woven roving (Eg) and Unidirectional carbon (UC). Fillers are graphite (G) and aluminum (AL) powders. The physical and mechanical properties for these raw materials are listed in tables 2, 3 and 4.

Table 2,
Physical and mechanical properties of (UP) resin [16].

Properties	Value
Density	1268 kg/m^3
Tensile strength	50 MPa
Modulus of elasticity	3 GPa
Elongation	2.5%
Barcol hardness	40

Table 3,
Physical and mechanical properties of fiber:
a- E-glass woven roving [17].

Properties	Value
Density	2580 kg/m^3
Tensile strength	3450 MPa
Modulus of elasticity	72 GPa
Poisson's ratio	0.22

b- Unidirectional carbon [18].

Properties	Value
Density	1790 kg/m^3
Tensile strength	3900 MPa
Modulus of elasticity	230 GPa
Poisson's ratio	0.2

Table 4,
Physical and mechanical properties of filler:
a- Aluminum powder [19].

Properties	Value
Density	2700 kg/m^3
Tensile strength	60 MPa
Modulus of elasticity	71 GPa
Thermal conductivity	247 w/m.°C
practical size	75 µm

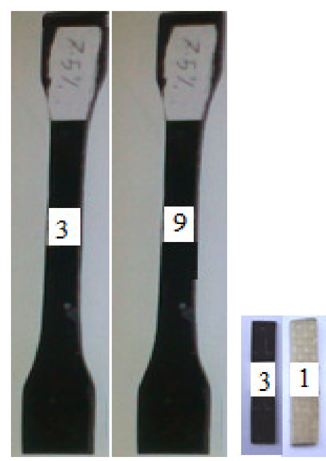
b- Graphite powder [19].

Properties	Value
Density	1780 kg/m^3
Tensile strength	40 MPa
Modulus of elasticity	11.7 GPa
Thermal conductivity	118 w/m.K
practical size	100 µm

Experimental design: Three parameters that (fiber volume fraction, filler and type of fiber) were considered with three levels for each, to optimize the composite plate mechanical properties, cost and weight. Table 5 shows these parameters with their levels. Taguchi technique to experimentation gives a regular way to collect data, interpret and analyze to satisfy the study objective. Selection of control factors is the most important stage in the experiment design. therefore, take care in choosing a suitable orthogonal array and control parameters with their levels, to get combination of optimum level [20, 21]. To study the impact of parameters in this work, L_9 (3^3) orthogonal design has been used as shown in table 6.

Specimens Preparation: specimens were manufactured by dry hand layup technique. Unsaturated polyester resin was mixed with the hardener in ratio 100:2 by weight. The powders filler was mixed with known amounts of unsaturated polyester resin. The stacking procedure of fiber-polyester composites was constructed by placing fiber ply one above other with resin mixed well to spread between plies using mold of (250x250x20) mm. The fiber orientation of unidirectional carbon was made with [0/90/0/90], whereas for (Eg+UC) was made by [Eg/0UC/Eg/90UC]. The whole assembly was pressed by (0.3 MPa) then released and allowed to cure for a 6 days at room temperature. The product is a composite plate.

The plates are cut into the appropriate dimensions using a tipped cutter, and then machining it by using a vertical milling CNC machine to manufacture a tensile tests specimens according to ASTM D 638-3 [22]. While, Charpy impact test specimens were performed according to ISO 179 [23] as shown in fig.1. These specimen's details are shown in table 6. Tensile test done using LARYEE tensile test machine, with 1000 kg applied load and (2mm/min) strain rate. While, Impact test done using LARYEE Charpy impact test machine. Tests carry out in laboratory of Material Eng. Dept./University of Technology.



-a- -b-

Fig. 1. Experimental test specimens:
a- Tensile test specimens.
b- Charpy impact test specimens.

Table 5,
Parameters with their levels.

Parameters	**Symbol**	**Levels of Parameter**		
		Level- 1	**Level- 2**	**Level- 3**
Type of fiber	A	Eg	UC	Eg+UC
Filler	B	0%	5%AL	7.5%G
Fiber volume fraction	C	27%	30%	33%

Table 6,
Experimental plan using orthogonal array L_9.

Exp. No.	Type of fiber- A		Filler- B		Fiber volume fraction - C	
	level	value	level	value	level	value
1	1	Eg	1	0%	1	27%
2	1	Eg	2	5%AL	2	30%
3	1	Eg	3	7.5%G	3	33%
4	2	UC	1	0%	2	30%
5	2	UC	2	5%AL	3	33%
6	2	UC	3	7.5%G	1	27%
7	3	Eg+UC	1	0%	3	33%
8	3	Eg+UC	2	5%AL	1	27%
9	3	Eg+UC	3	7.5%G	2	30%

(Parameters and level)

4. Results and Discussion

Aerodynamic forces: The aerodynamic loading under the cruise flight conditions can simply be defined as, the load acting on the aircraft will be equivalent to the weight of the structure. Lift load on the aircraft structure is normally distributed as 80% on wings and remaining 20% on the fuselage [24]. Since, the aircraft take-off weight under design is 30kg. Therefore, the total load acting on the wings will be equal to (300 × 0.8 = 240N). The load acting on each wing will be 120N. Since, the aerodynamic load is applying on the center of pressure of wing located at ¼ chord from leading edge. Using finite element method (ANSYS-11 software) to investigate the effect of (120N) on the wing. The results represent the von Misses stress distribution shown in fig. 2, and it is found that the maximum stress is 40 MPa.

Experiment results: After preparing all the nine specimens for each test. Experimental tests were conducted use tensile test machine and Charpy impact test machine. Each experiment was repeated three times and then compute the average value. The Modulus of elasticity, Fracture toughness, and tensile strength are the mechanical properties that investigated here. The experimental results for each specimen with their calculated density was listed in table 7. The density of a composite material can be calculated using [25].

$\rho_c = \sum V_i \rho_i = V_1.\rho_1 + V_2.\rho_2 + \dots + V_n.\rho_n$ …(1)

Where:
ρ_c: density of composite material.
ρ_1, ρ_2, ρ_n: density of each constituent.
V_1, V_2, V_n: volume fraction of each constituent.

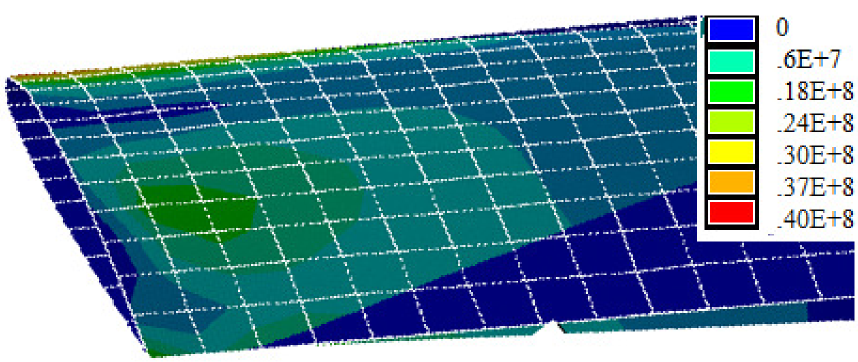


Fig. 2. von Misses stress distribution on wing.

Table 7,
Experimental results and their signal-to-noise ratio.

Exp. No.	Modulus of Elasticity GPa	Modulus of Elasticity S/N dB	Tensile strength MPa	Tensile strength S/N dB	Toughness MPa√m	Toughness S/N dB	Density Kg/m^3	Density S/N dB
1	2.612	8.339	129	42.212	16.570	24.386	1622.24	-64.202
2	5.201	14.322	174.53	44.837	19.633	25.860	1733.2	-64.777
3	8.340	18.423	201.40	46.081	21.456	26.631	1739.36	-64.808
4	14.373	23.151	315.21	49.972	26.750	28.546	1424.6	-63.074
5	23.639	27.473	480.49	53.634	32.192	30.155	1511.86	-63.590
6	24.401	27.748	500.84	53.994	34.047	30.642	1447.34	-63.211
7	14.425	23.182	240.74	47.631	20.892	26.400	1570.61	-63.921
8	12.247	21.761	357.24	51.059	26.306	28.401	1587.19	-64.013
9	16.307	24.247	467.32	53.392	30.146	29.585	1581.5	-63.981

Signal to Noise Ratio (S/N): Signal to noise ratio measures sensitivity of the quality investigated to those uncontrollable factors (error) in the experiment. Using “bigger is better” quality characteristic for mechanical properties investigation, while “smaller is better” used for density analysis to get high strength/weight ratio. The following logarithmic equation used to perform S/N ratio analysis [26].

1. “bigger is better”,

$$S/N = -10\ log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \qquad ...(2)$$

2. “smaller is better”,

$$S/N = -10\ log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}y_i^2\right] \qquad ...(3)$$

Where: n is the observations number.
y_i is the data observed.

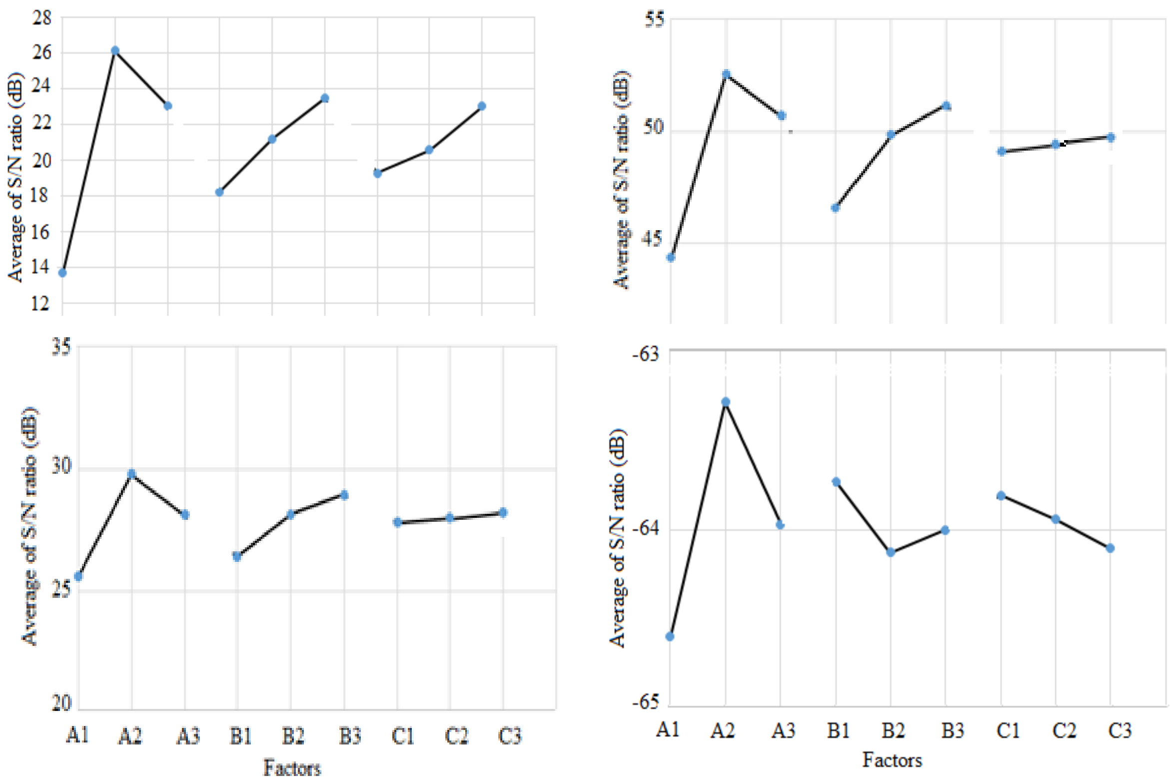
For all nine experiment readings, the S/N ratios were calculated and listed in table 7. From table 7, it can be seen that, experiment number 6 has the largest mechanical properties S/N ratio. The parameters combination with their level in this experiment is $A_2B_3C_1$. Whereas experiment number 4 show the smallest density value, and the parameters combination with their level is $A_2B_1C_2$. According to the results of combinations generated from orthogonal array. The optimum levels were predicted by estimating the control factors for different three levels. The control factors levels were determined and listed in table 8. Fig. 3 shows the distributions of average S/N ratios. Where the goal for mechanical properties is “bigger is better”, from fig. 3 it can be noticed that, the optimal parameters combination with their levels is $A_2B_3C_3$, equivalent to (carbon fiber, 7.5%G filler and 33% fiber volume fraction), which get a higher characteristic of modulus of elasticity, tensile strength and toughness. While $A_2B_1C_1$ is the optimal parameters combination with their levels for density to get “smaller is better”, that equivalent to (carbon fiber, 0% filler and 27% fiber volume fraction).

Table 8,
Average signal to noise ratio of different parameter levels.

Parameter	Symbol	Average of S/N (dB) of different parameter levels: Level - 1	Level - 2	Level - 3	Max - Min	optimum level
Modulus of Elasticity						
Type of fiber	A	13.6948	26.1239	23.0635	12.4291	
Filler	B	18.2242	21.1850	23.4730	5.2487	$A_2B_3C_3$
Fiber volume fraction	C	19.2827	20.5734	23.0261	3.7433	

Tensile strength						
Type of fiber	A	44.3768	52.5332	50.6942	8.1564	
Filler	B	46.6049	49.8434	51.1558	4.5509	$A_2B_3C_3$
Fiber volume fraction	C	49.0883	49.4006	50.1153	0.3122	
Toughness						
Type of fiber	A	25.6257	29.7810	28.1284	11.7167	
Filler	B	26.4442	28.1386	28.9524	4.2933	$A_2B_3C_3$
Fiber volume fraction	C	27.8097	27.9969	28.0185	1.3471	
Density						
Type of fiber	A	-64.5957	-63.2918	-63.9718	11.7167	
Filler	B	-63.7325	-64.1266	-64.0002	4.2933	$A_2B_1C_1$
Fiber volume fraction	C	-63.8088	-63.9441	-64.1065	1.3471	

Underlined value represents the optimum level.



c-Toughness

d-Density

Fig. 3. Main effect graph.

Analysis of Variance (ANOVA): ANOVA is a statistical method in which used for predicting the individual interactions of all control parameters. In this research, ANOVA used to analyze the influence of fiber volume fraction, filler and type of fiber on the mechanical properties and density of composite material plates. In the analysis, to measure the corresponding effects on the quality characteristics, use the percentage distributions of each control parameter [27]. Table 9, present the mechanical properties and density results using ANOVA analysis. From these results it can be found that the significant parameter is the type of fiber, followed by filler and then the fiber volume fraction. The type of fiber contributions to mechanical properties and density are exceed 70% and 80% respectively.

Table 9,
ANOVA results of mechanical properties and density.

Parameters	Sum of Squares (SS)	Degree of Freedom (df)	Mean Squares (MS)	F value	Contribution (%)
Modulus of Elasticity					
Type of fiber	251.6187	2	125.8094	54.7421	78.76
Filler	41.5502	2	20.7751	9.0397	13.01
Fiber volume fraction	21.6940	2	10.8470	4.7197	6.79
Error	4.5964	2	2.2982		1.44
Total	319.4594	8			100.00
Tensile strength					
Type of fiber	109.8185	2	54.9092	78.1765	76.09
Filler	32.9210	2	16.4605	23.4355	22.81
Fiber volume fraction	0.1796	2	0.0898	0.1279	0.12
Error	1.4048	2	0.7024		0.97
Total	144.3238	8			100.00
Toughness					
Type of fiber	26.260	2	13.130	104.590	72.05
Filler	9.8244	2	4.9122	39.1281	26.95
Fiber volume fraction	0.1137	2	0.0568	0.4528	0.31
Error	0.2511	2	0.1255		0.69
Total	36.4501	8			100.00
Density					
Type of fiber	2.5516	2	1.2758	692.407	87.04
Filler	0.2429	2	0.1215	65.9229	8.29
Fiber volume fraction	0.1333	2	0.0667	36.1732	4.55
Error	0.0037	2	0.0018		0.13
Total	2.9315	8			100.00

5. Confirmation Test

The optimum combinations parameters of processes with their levels were found using Taguchi technique. But the optimum combinations did not match any experiment from experiments in orthogonal array. Therefore, it is necessary to confirm results of Taguchi technique with experimental results for the optimum combinations.

The mechanical properties and density values at the optimum condition were predicted through use the optimum process parameters level [28]. The optimum combination parameters of mechanical properties are ($A_2B_3C_3$), in which equivalent to (carbon fiber, 7.5%G filler and 33% fiber volume fraction). Whereas the optimum combination parameters of density are ($A_2B_1C_1$), that represent (carbon fiber, 0% filler and 27% fiber volume fraction). The S/N ratio of optimum combination process parameters can be predicted using the following equation [21]:

$$\eta_{opt} = \eta_m + \sum_{i=1}^{j} (\eta_i - \eta_m) \qquad \dots (4)$$

Where:

η_{opt}: predicted S/N ratio.

η_m: Total mean of S/N ratios.

η_i: mean S/N ratio at optimum levels.

j: number of main design parameters that affact the quality characteristics.

The predicted results were listed in table 10. Tensile and Charpy impact test specimens then prepared for the optimum combination parameters, and experiments of (tensile test and Charpy impact test) had been done for mechanical properties, while its density was estimated. The results are shown in table 10. The results show that, the experimental and the predicted results are very close, with error not exceed 7.5%. This verify that the experiment result is correlated with the predicted result.

From experiments and Taguchi technique analysis, turns out the optimum combination parameters. Without refer to the cost, but the cost is one of the most important factors that influence the selection of materials in engineering applications. The cost of unsaturated polyesters is approximately the same for all samples, as well as the cost of additives are very few in comparison with the fiber cost. Therefore, it will be a focus on fiber as an effective parameter in the selection. It is necessary to optimize between the cost, weight (density) and mechanical properties. The combination parameters (carbon fiber, 7.5%G filler and 33% fiber volume fraction), gives higher mechanical properties with a very agreement density of (1478 kg/m^3), but higher cost, because the cost of carbon fiber is approach to 20th times the cost of E-glass fiber.

The results of using finite element method showed that, the maximum stress on the wing is 40 MPa. So, from table 7, and the optimum combinations parameters, it can be choosing the combination parameters in which get the required selection. Experiment number 9, present agreement combination parameters for the composite plate selection. This combination provides good mechanical properties, high safety factor, acceptable cost, and offers weight savings on average by 40% percent as compared to aluminum alloy. The parameters combinations of this experiment are ((Eg+UC) fiber, 7.5% G filler and 30% fiber volume fraction).

Table 10,
Confirmation results

characteristic	Optimum Parameter			
	Level	Experiment	Predication	Difference (%)
Modulus of Elasticity (GPa)	$A_2B_3C_3$	32.644	34.282	4.7
Tensile strength (MPa)	$A_2B_3C_3$	548.627	542.426	1.1
Toughness (MPa)	$A_2B_3C_3$	32.9507	35.646	7.5
Density (kg/m^3)	$A_2B_1C_1$	1408.94	1400.700	0.57

6. Conclusions

From the results obtained in this work the following can be concluded:

1. The type of fiber is the significant parameter effect on the composite plate selection, followed by filler and finally the fiber volume fraction parameter.
2. The type of fiber parameter contributions on mechanical properties exceed 70%, while on density it is exceed 80%.
3. The optimum combination parameters with their levels of mechanical properties are (carbon fiber, 7.5 Graphite filler, and 33% fiber volume fraction). Whereas, the optimum combination parameters of weight are (carbon fiber, 0% filler, and 27% fiber volume fraction)
4. The agreement combination parameters with their levels are ((Eg+UC) fiber, 7.5% Graphite filler and 30% fiber volume fraction). This combination provides good mechanical properties, high safety factor, acceptable cost, and offers weight savings on average by 40% percent as compared to aluminum alloy.

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تحليل الخواص الميكانيكية للمواد المركبة عند تغيير عوامل مختلفة

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الخلاصة

ان الهدف من هذا البحث هو تصميم واختيار صفيحة مواد مركبة تستخدم في غشاء جناح طائرة خفيفة بدون طيار (UAV) .. اعتمدت الخواص الميكانيكية والوزن والكلفة معيارا لهذا الاختيار. ان الكسر الحجمي للألياف والاضافات ونوع الألياف هي العوامل التي اخذت بالاعتبار مع ثلاثة مستويات لكل منها للمفاضلة في اختيار الصفيحة. تم استخدام طريقة العناصر المحددة لإيجاد توزيع الاجهاد على الجناح وحساب الاجهاد الأقصى. استخدمت تقنية تاجوشي لتصميم التجارب. يمكن إيجاد العناصر ذات الأثر الأكبر في عملية الاختيار باستخدام المصفوفة المتعامدة L_9 ونسبة الإشارة الى الضوضاء وتحليل التباين (ANOVA). تظهر النتائج أن النتائج العملية قريبة جدا من النتائج المحسوبة. وان عامل نوع الألياف له الأثر الأكبر في اختيار الصفيحة تليها الإضافات ومن ثم الكسر الحجمي للألياف. وان أفضل مجموعة عناصر هي عند استخدام ((الياف زجاجية + ألياف الكربون أحادي الاتجاه) مع ٧.٥٪ كرافيت و٣٠٪ كسر حجمي للألياف) والتي تعطي خواصا ميكانيكية جيدة وعامل أمان عال وكلفة مقبولة مع خفض الوزن بنسبة ٤٠٪ بالمقارنة مع سبائك الألومنيوم.