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Stiffness to Weight Ratio of Various Mechanical and Thermal Loaded Hyper Composite Plate Structures

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Abstract. In this study, several models of the rocket fins were made of hyper composite materials (with two or more reinforced materials) with different volume fractions of components used to produce isotropic composite plate structures. The reinforcement of polyester resin material was done in two ways, with fibre reinforcement and powder reinforcement. The types of fibres that used were chopped glass fibre and chopped carbon fibre, and the type of powder used was carbon powder. A concentrated load was applied to the models in the form of a cantilever plate. The effect of adding carbon powder on the stiffness to weight ratio and the effect of temperature on this stiffness to weight ratio were studied and discussed. It was observed that hybridization improves the properties of composite materials at certain specific volume fractions of carbon powder. The best percentage of improvement of the value of stiffness was 69.87% in a specimen made of 50% polyester, 30% glass fibres, and 20% carbon powder in terms of models reinforced with glass fibres, while for models reinforced with carbon fibres, it was 79.94% in the model made of 60% polyester, 30% carbon fibre, and 10% carbon powder. In addition, the results showed that an increase in temperature leads to a decrease in the stiffness to weight ratio for all models. The smallest effect of temperature on the stiffness to weight ratio was shown in the sample composed of 50% polyester, 30% glass fibres, and 20% carbon powder, at 45.83% for the models reinforced with chopped glass fibres, and in the model made of 60% polyester, 20% carbon fibres, and 20% carbon powder at 57.54% for models reinforced with carbon fibres.

Keywords: Hyper composites, rocket fin, thermal loading, stiffness to weight ratio.

1. INTRODUCTION

Hyper composite materials are among the most adaptable and advanced engineering materials currently available. They are heterogeneous material created by mixing two or more components with reinforcing fibres or fillers and a compactable matrix. They can thus provide unique and superior physical and mechanical properties by combining the most desirable properties of their constituent parts while suppressing their less desirable properties [1]. There are three kinds of hyper composite: matrix hyper, fibre hyper, and interfacial hyper. A matrix hyper refers to combining of two or more types of resin in one composite; a fibre hyper means that different fibres are used in a single textile; while interfacial hyper refers to combining of two or more types of fibre bundles with various surface treatments. The mechanical properties of these hyper composites (high specific strength, high specific stiffness, good energy absorption, low density, and good corrosive resistance) vary according to changes in volume ratio and the stacking succession of different layers [2].



M. Akhbar et al. [3] improved the buckling strength of material by using two types of reinforced fibre (glass and polyester fibres) to produce a new hybrid composite material. **Heitor Luiz Ornaghi et al.** [4] evaluated the performance of hybrid composite materials consisting of glass/sisal fibres and polyester resin, wherein it was observed that the mechanical properties such as flexural and impact analysis were increased. **G. Velmurugan et al.** [5] evaluated the mechanical (flexural, impact, and tensile strength) properties of hybrid composite materials composed of epoxy resin reinforced with coir and sisal fibres and proved that this type of material was suitable for low loads and lightweight applications. **R.T. Durai Prabhakaran et al.** [6] studied hybridization's effects on the compression and tensile properties of a hybrid composite material composed of epoxy and unidirectional fabric (carbon and glass) fibres, observing that the hybrid composite offered better compression and tensile properties in comparison to the glass/epoxy specimen or carbon/epoxy specimen. **M. J. Jweeg et al.** [7] experimentally determined the modulus of elasticity for long, short, woven, powder, and particle reinforcement of composite materials with different volume fractions, showing that the best modulus of elasticity for reinforcement composites was found in unidirectional fibre types in the longitudinal direction and woven reinforcement types in the transverse direction. **M.J. Jweeg** [8] further presented an analytical solution for the vibration of honeycombs for combined structures to evaluate natural frequencies, whereby the length, height, and angle of regular hexagonal honeycomb structure was varied for parametric study purposes using the suggested analytical solution. The use of composite materials is common in many applications, including aircraft, marine applications, and aerospace, so studying the effect of ambient conditions such as temperature on the mechanical and thermal properties of these materials is very important [9]. **Radoljub P. et al.** [10] thus studied the influence of temperature during the manufacturing process on carbon/epoxy composite material in terms of the residual stresses during curing and cooling. **Adnan Naji et al.** [11] carried out a theoretical buckling analysis of composite material under thermo-mechanical loads. It was observed that the critical buckling load decreased when the aspect ratio increased, and that the maximum reduction occurred when the aspect ratio was varied from 0.5 to 2. **Al-alkawi Hussain et al.** [12] investigated the strength and tensile modulus at various temperatures (room temperature, 0°, -15°, and -30°) of a composite material that used 60% by volume fraction carbon fibre reinforced aluminium as a matrix. **Al-Shammri, M and Emad, S** [13] studied the effects of adding carbon powder on the deflection of irregular hyper composite plates made of polyester and glass fibre under thermal and mechanical loading. It was observed that the addition of the carbon powder led to a decrease in deflection in the plates; this deflection increased with temperature increases.

The goal of the current research is to manufacture several models of hybrid composite plate (rocket fin) and thus to evaluate the stiffness to weight ratio and the effect of temperature on this ratio. The models were all made of unsaturated polyester, with different volume fractions of fibreglass or carbon fibres and carbon powder.

2. Numerical analysis

The analytical solution to plate bending depends on the design parameter of the plate, including geometry, boundary conditions and load configuration; thus, if these parameters are too complicated, the analytical solution will also become complicated. In cases with complex structures, a numerical solution is used to verify the experimental results. The finite element method is a muscular computational technique increasingly used to obtain the solution to integral and differential equations in most fields of science and engineering [14]. The dimensions and the shape of the rocket fin model used in this study is shown in Figure 1 [15]. The deflection of the fin model is analysed using the finite element method by employing the ANSYS program (version 15). The nodal solution of the displacement and stress are shown in Figure 2.

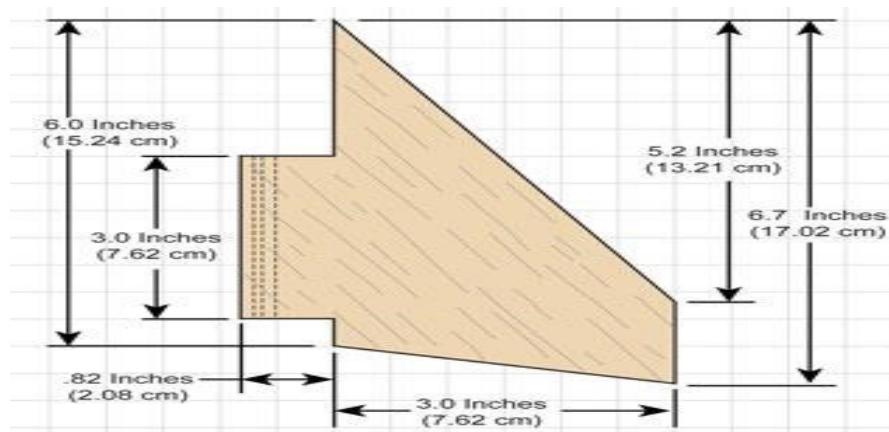


Figure 1. The dimensions and shape of the rocket fin[16].

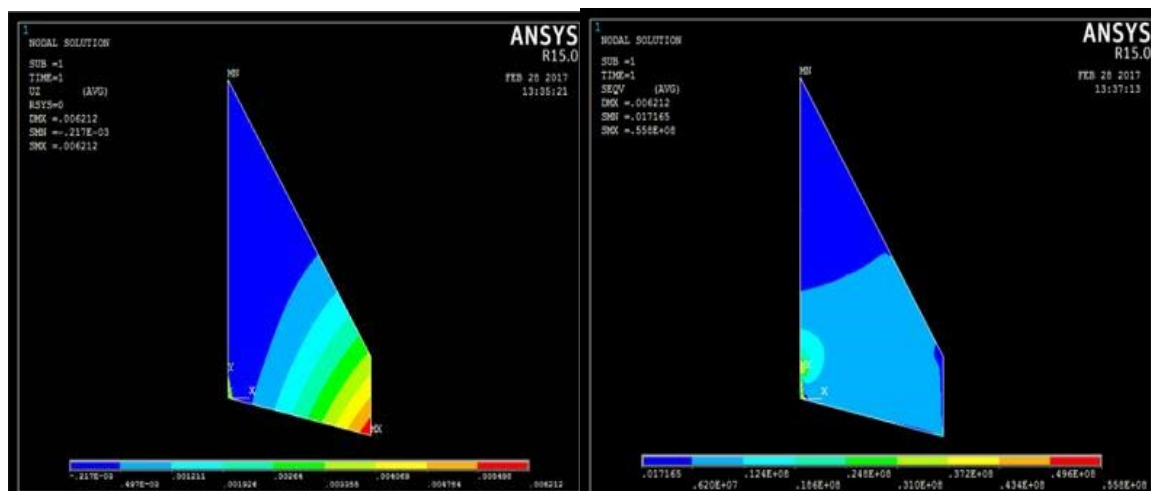


Figure 2. The nodal solutions for displacement and stress.

3.Experimental work

The general steps to prepare the moulds and manufacture the specimens and the rocket fin models made of the hyper composite materials with polyester resin, glass or carbon fibres, and carbon powder with different volume fractions are shown in Figure 3. A bending rig was built to evaluate the maximum deflection by applying a concentrated load on these models, and the effect of adding carbon powder and the effect of temperature on the maximum deflection were studied. The temperature range was chosen based on matrix ability and application.

Table 1 shows the volume fraction of the components of the manufactured models.

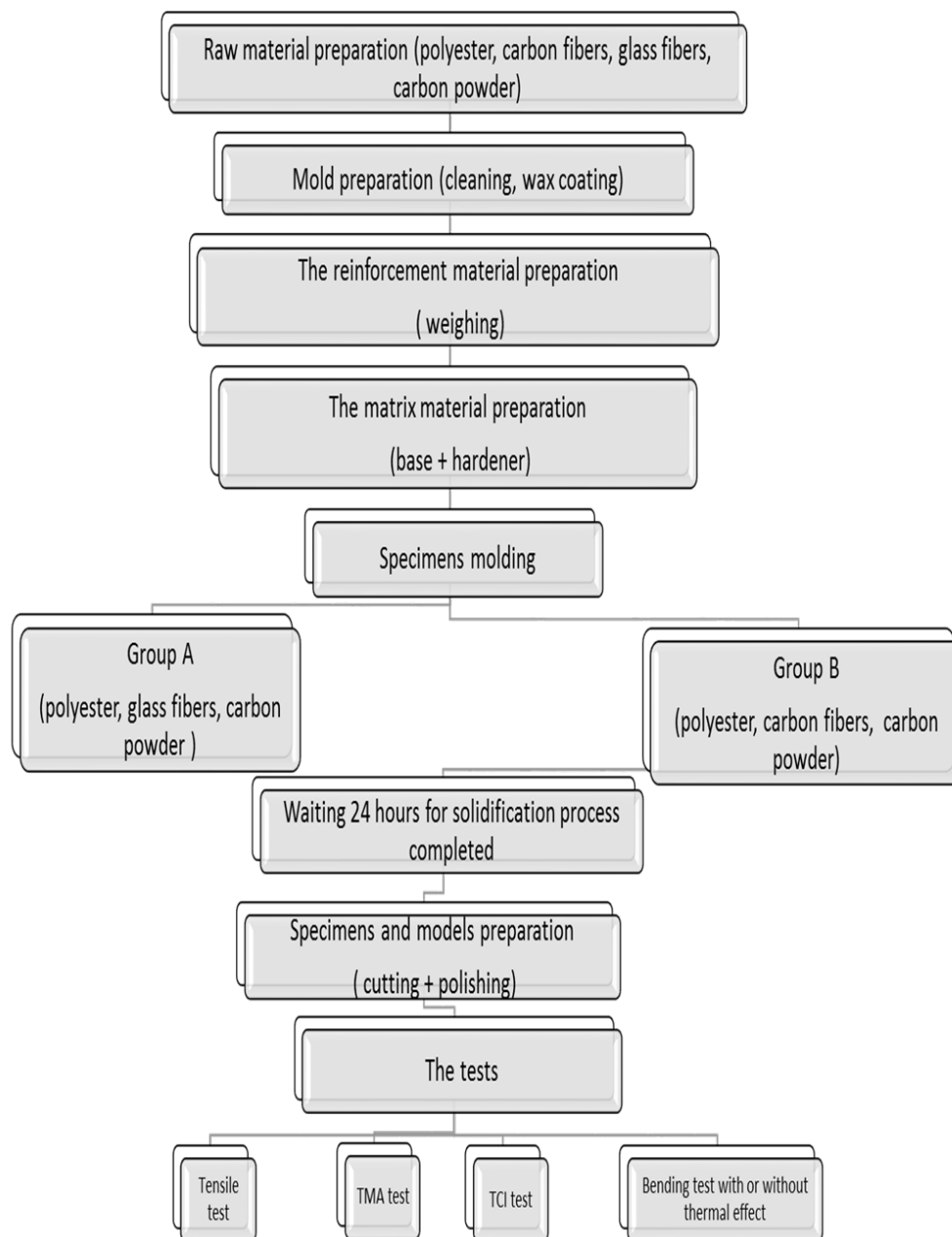


Figure 3. Flow chart of experimental work.

Table 1. The volume fraction of the components of the manufactured models.

Sample No.	Type of fibres	Volume fraction of fibres V_f %	Volume fraction of carbon powder V_p %	Reinforcement volume fraction (V_f+V_p) %	Volume fraction resin V_r %
1	Glass fibres	30	0	30	70
2		25	5	30	70
3		20	10	30	70
4		10	20	30	70
5		30	10	40	60
6		20	20	40	60
7		10	30	40	60
8		40	10	50	50
9		30	20	50	50
10		20	30	50	50
11		10	40	50	50
12	Carbon fibres	30	0	30	70
13		25	5	30	70
14		20	10	30	70
15		10	20	30	70
16		30	10	40	60
17		20	20	40	60
18		10	30	40	60
19		40	10	50	50
20		30	20	50	50
21		20	30	50	50
22		10	40	50	50

3.1 Materials

Unsaturated polyester was used as a matrix in this study. This took the form of a viscous transparent liquid of the thermosetting polymer type. It was converted into a solid by mixing it with hardener (2% of polyester weight). The types of fibres used were E-glass (chopped) and carbon fibres, and the type of powder was carbon powder (avg. diameter 109.86 nm). The mechanical properties of these materials are shown in Table 2.

Table 2. Mechanical properties of the materials used [68].

Materials	Modulus of Elasticity, E (GPa)	Poisson's Ratio, ν	Density, ρ (kg/m ³)
Glass fibres	74	0.25	2500
Carbon fibres	230	0.2	1800
Polyester	2.5 - 4	0.4	1200

3.2 Manufacturing of specimens and rocket fin models

The models of rocket fins which were manufactured in this research are shown in Figure 4.



Figure 4. Manufactured models of rocket fins: see table 1 for composition specifics.

3.3 Bending Test

The aim of this test was to identify the linear behaviour of the materials under the influence of a load applied vertically to the surface plane. The bending test included the determination of the value of deflection that occurred because of applying the load. The bending structure rig consisted of the following parts: a metal vice, a dial indicator, a load cell, a power supply, an electric furnace, and a thermos-reader with thermocouples as shown in Figure 5.

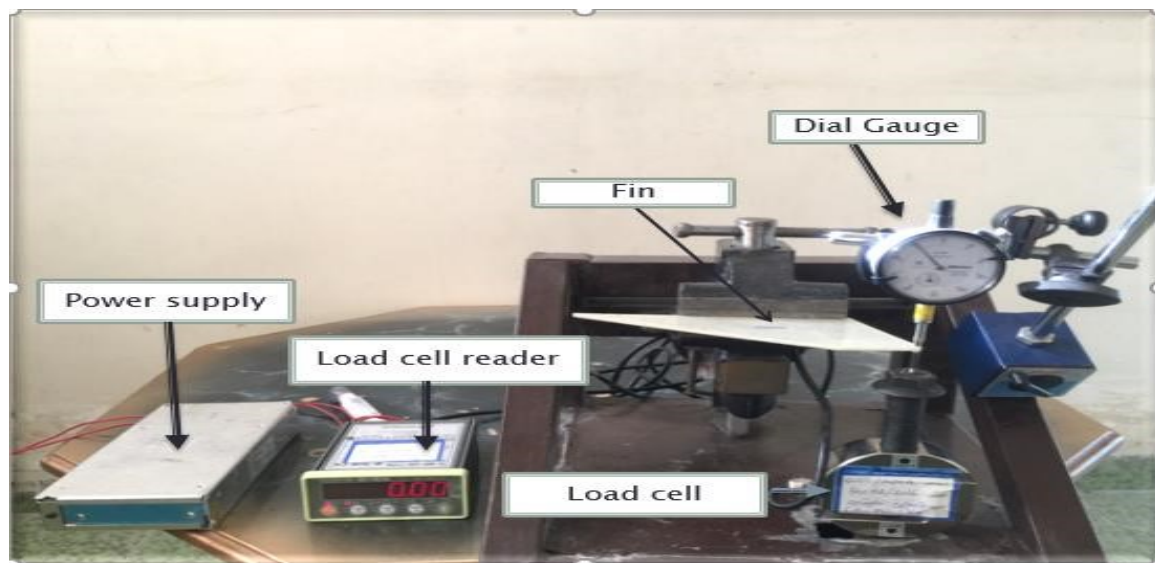


Figure 5. Bending structure rig.

4. Results and discussion

4.1 Mechanical loading on rocket fin models:

Twenty-two models of rocket fins were tested by applying a concentrated load at the end of the fin; the maximum deflection was first calculated without considering the effect of temperature, and then the effect of temperature was added. The results were calculated numerically using the ANSYS program and experimentally by constructing a rig to measure this deflection. The numerical and experimental results are listed in tables 3 and 4 for the first and second groups, respectively.

The load value applied on the fins was 19.62 N, chosen as a value that could be sustained by all the fins without causing failure. The distribution of stress for the fins under this load is shown in Figure 6. In the case of added thermal effects, the value was reduced to 14.715 N in order to measure the deviation of all fins without failure or exceed the range of dial gauge. Figure 7 shows the method used to fix the load (cantilever) and the point of force application. From these tables, it is clear that increasing in the volume fraction of carbon powder increased deflection at all percentages unless the specimens contained 30% glass fibres; the deflection decreased with an increase of carbon powder, and for reinforcement with 30% carbon chopped fibres, it decreased until the addition of 10% carbon powder was reached, increasing after this percentage. These behaviours are happened occur because carbon powder has high values of tensile strength and flexibility compared with the glass fibre, and can be easily randomly distributed into the polyester material; the ease of penetration of the matrix material into the powder and fibre creates a more solid interface between the matrix and reinforcement material. However, when the volume fraction of the powder is increased, it leads to reduction in the value of the Young's modulus because of the difficulty of penetration of the matrix material into powder and fibre, which leads to a weakening of the relationship between matrix and fibre, thus reducing the efficiency of carrying the applied load on the composite plate.

It was observed that fins reinforced with glass fibres had higher deflection values when compared with fins reinforced with carbon powder; this is because the carbon fibre has a Young's modulus higher than that of fibreglass, and this is inversely proportional to maximum deflection unless the fins are reinforced with 30% fibres and contain a volume fraction of carbon powder greater than 17%. At these percentages, the values of deflection are equal for both types of reinforcement (glass or carbon) as their Young's modulus is equal at this point. The lower value of deflection in models reinforced with glass fibres was 2.21 mm; this occurred in model no. 9, which was manufactured of 50% polyester, 30% glass fibres, and 20% carbon powder. In the models reinforced with carbon fibres the lowest value was 1.48 mm, which occurred in model no. 16, manufactured of 60% polyester, 30% carbon fibres, and 10% carbon powder.

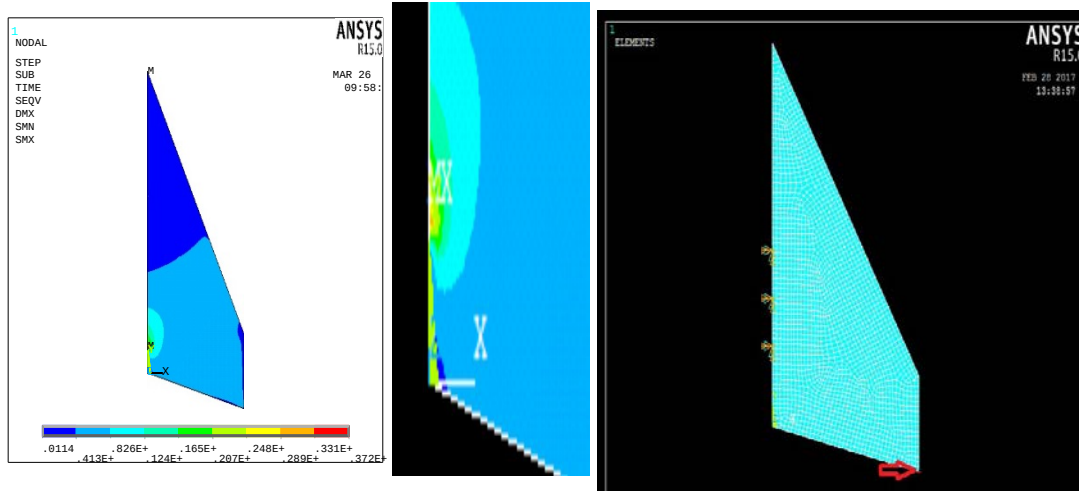


Figure 6. The stress distribution on the model. **Figure 7.** The method of fixing the load.

Table 3. Experimental and numerical results for maximum deflection of rocket fin models reinforced with glass fibre under mechanical loading.

Model no.	Volumefraction of resin	Volumefraction of reinforcement	Volume fraction of fibre	Volume fraction of carbon powder	Hyper composite combined of glass fibre, carbon powder, and polyester resin		
					Maximum deflection (mm) Numerically	Maximum deflection (mm) Experimentally	Error %
1	70	30	30	0	4.14	3.91	5.55%
2			25	5	3.36	3.18	5.35%
3			20	10	3.02	2.77	8.27%
4			10	20	5.52	5.18	6.15%
5	60	40	30	10	2.67	2.5	6.36%
6			20	20	4.33	4.03	6.9%
7			10	30	5.41	5.09	5.91%
8	50	50	40	10	2.54	2.29	9.84%
9			30	20	2.21	2.08	5.88%
10			20	30	4.58	4.33	5.45%
11			10	40	8.14	7.98	2 %

Table 4. Experimental and numerical results for maximum deflection of rocket fin models reinforced with carbon fibres under mechanical loading.

Model no.	Volume fraction of resin	Volume fraction of reinforcement	Volume fraction of fibre	Volume fraction of carbon powder	Hyper composite combined of carbon fibre, carbon powder, and polyester resin		
					Maximum deflection (mm) Numerically	Maximum deflection (mm) Experimentally	Error %
12	70	30	30	0	2.64	2.51	4.9%
13			25	5	2.67	2.47	10.8%
14			20	10	2.92	2.71	7.19%
15			10	20	4.14	3.79	8.45%
16	60	40	30	10	1.48	1.37	7.43%
17			20	20	3.23	3.02	6.5%
18			10	30	4.36	4.15	4.81%
19	50	50	40	10	1.63	1.49	8.58%
20			30	20	3.03	2.82	6.93%
21			20	30	3.35	3.12	6.86%
22			10	40	5.63	5.31	5.68%

4.2 The stiffness to weight ratio of the rocket fins

The values of the stiffness to weight ratios of the fins were obtained from tables as shown in table 5 and 6, which represent the effect of mechanical loads on the fins as ascertained by applying different loads and measuring the maximum deflection.

Figure 8 shows the effect of carbon powder on the stiffness to weight ratio of rocket fins with different volume fraction values.

From Figure 10, it is clear that adding carbon powder leads to a decrease in the value of the stiffness to weight ratio for all percentages of fibre except in models reinforced with 30% glass fibres, where it increased until it reached 10% carbon powder; after that, it decreased. From this figure, it can be inferred that the critical volume fraction for the models reinforced with glass fibres is 10%. This behaviour occurs due to the fact that the increase in the volume fraction of the powder leads to a decrease in the cross linkages within the material and facilitates crack movements which are caused by loosening of the bonds between the molecules of the material.

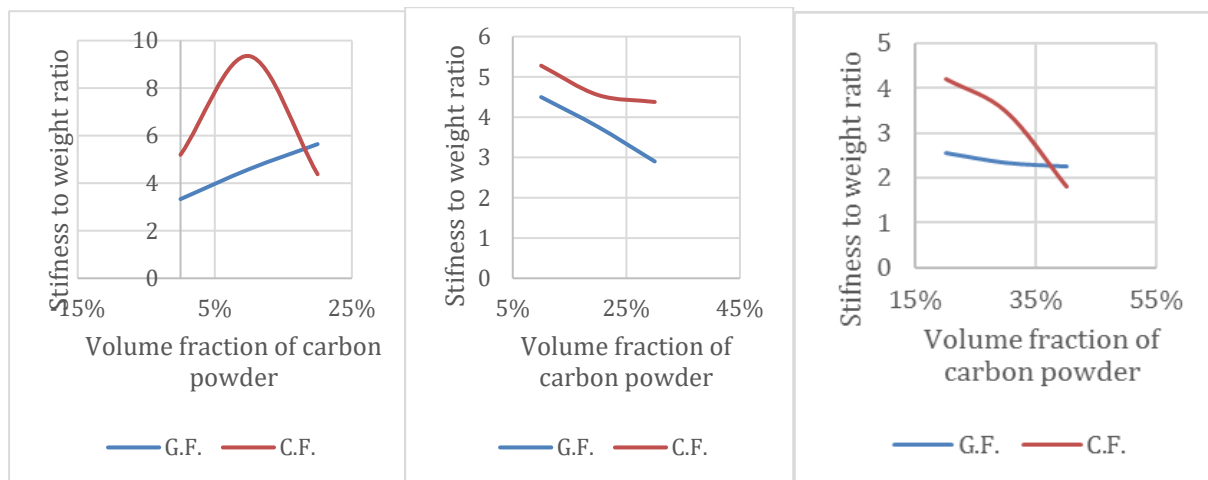
The maximum percentage of improvement in the value of the stiffness to weight ratio was 69.87 in model no. 9 with regard to models reinforced with glass fibres, while for models reinforced with carbon fibres, it was 79.94% in model no. 16.

Table 5. Maximum deflection of models reinforced with glass fibres under mechanical load

Model no.	Maximum deflection (mm) under 9.81 N			Maximum deflection (mm) under 14.715N			Maximum deflection (mm) under 19.62 N			Maximum deflection (mm) under 29.43 N		
	Exp.	Num.	Error	Exp.	Num.	Error	Exp.	Num.	Error	Exp.	Num.	Error
1	1.7	1.9	10.05%	2.69	3.1	13.2%	3.61	3.8	5%	5.67	5.8	2.24%
2	1.45	1.56	7.05%	2.36	2.52	6.34%	3.28	3.36	2.43%	5.04	5.47	6.03%
3	1.3	1.51	14%	2.12	2.27	6.6%	2.94	3.02	2.64%	4.54	4.92	7.7 %
4	2.32	2.42	4.13%	3.94	4.14	4.83%	5.58	5.52	2.5%	9.07	9.28	2.26%
5	1.24	1.33	6.76%	1.87	2	9.35%	2.5	2.67	6.36%	4.01	4.21	4.75%
6	1.78	1.95	8.71%	3	3.25	7.67%	4.13	4.33	4.61%	6.49	6.86	5.39%
7	2.5	2.7	7.4%	3.89	4.03	7.85%	5.25	5.41	2.95%	8.12	8.73	6.98%
8	1.13	1.27	11%	1.76	1.91	7.85%	2.35	2.54	8%	3.82	3.98	4.02%
9	0.95	1.1	13.36%	1.52	1.66	8.43%	2.12	2.21	4.07%	3.32	3.52	5.68%
10	1.98	2.29	13.5%	3.23	3.44	6.1%	4.43	4.58	3.27%	6.88	7.25	5.1%
11	3.6	4	10%	5.85	6.11	4.25%	8.48	8.14	4.66%	-	-	

Table 6. Maximum deflection of models reinforced with carbon fibres under mechanical load.

Model no.	Maximum deflection (mm) under 9.81 N			Maximum deflection (mm) under 14.715N			Maximum deflection (mm) under 19.62 N			Maximum deflection (mm) under 29.43 N		
	Exp.	Num.	Error	Exp.	Num.	Error	Exp.	Num.	Error	Exp.	Num.	Error
12	1.18	1.32	10.6%	1.76	1.98	11.11%	2.54	2.64	3.78%	3.85	3.96	2.85%
13	1.34	1.46	8.2%	1.88	2	6%	2.6	2.76	5.79%	3.81	4	4.75%
14	1.4	1.53	8.49%	1.91	2.15	11.16%	2.78	2.92	4.79%	4.18	4.38	4.56%
15	1.6	1.9	10.5%	2.47	2.58	4.26%	3.47	3.8	8.6%	5.62	5.8	3.1%
16	0.64	0.74	13.5%	1.23	1.11	10.8%	1.38	1.48	6.7%	2.02	2.18	7.3%
17	1.42	1.61	11.8%	2.13	2.02	6.5%	3.01	3.23	6.8%	4.66	4.85	3.9%
18	1.82	2.18	11.9%	3.14	3.27	3.97%	4.15	4.36	4.81%	6.13	6.53	6.12%
19	0.7	0.81	13.5%	1.08	1.2	10%	1.52	1.63	6.74%	2.05	2.35	12.7%
20	1.34	1.51	12.6%	2.19	2.27	3.5%	2.82	3	6%	4.32	4.55	5.05%
21	1.45	1.67	13.1%	2.41	2.5	3.6%	3.12	3.35	6.86%	4.83	5.02	3.78%
22	2.38	2.81	8.18%	3.4	3.59	3%	5.35	5.63	4.9%	8.9	8.44	5.45%



30% fibres 20% fibres 10% fibres

Figure 8. The effect of adding carbon fibres on the stiffness to weight ratio of fins

4.3 Effects of thermal loading on the stiffness to weight ratio

Tables (7) and (8) represent the stiffness to weight ratios of the fins under thermal loading for models reinforced with glass fibres and carbon fibres, respectively.

Figure (9) shows the effect of temperature on the stiffness to weight ratio of the rocket fins reinforced with chopped glass fibres and Figure(10) shows the effect of temperature on the stiffness to weight ratio of the rocket fins reinforced with chopped carbon fibres. From these figures, it is clear that an increase in temperature leads to a decrease in the values of the stiffness to weight ratio for all models. The decrease in the value of the stiffness to weight ratio may be due to the fact that increasing the temperature of the material leads to a weakening of the molecular chains of the matrix material, making it become softer, and this could produce additional strain leading to the decrease.

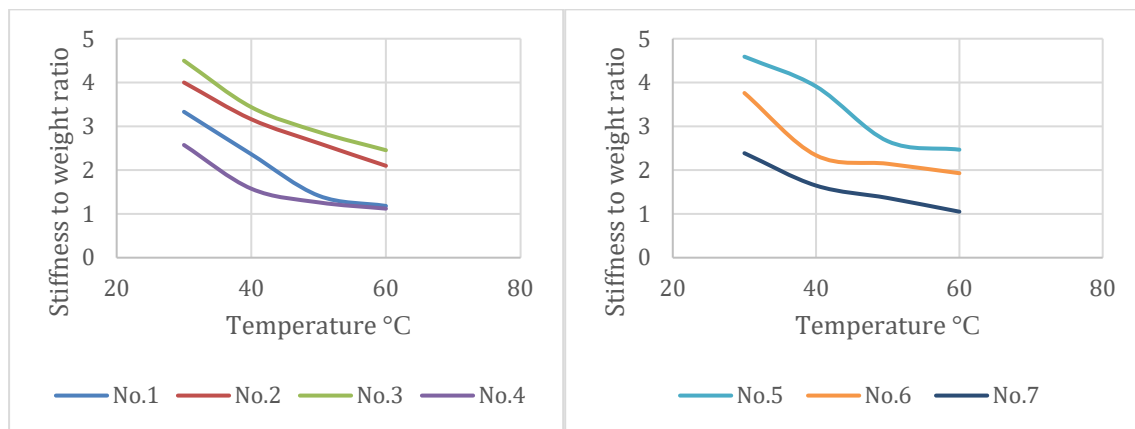
The smallest effect of temperature on the stiffness to weight ratio for the models reinforced with chopped glass fibres was shown by model No. 10, at 45.83%, and for models reinforced with carbon fibres, it occurred in model No. 17, at 57.54%.

Table 7. The effect of temperature on the stiffness to weight ratio of fins reinforced with glass fibres

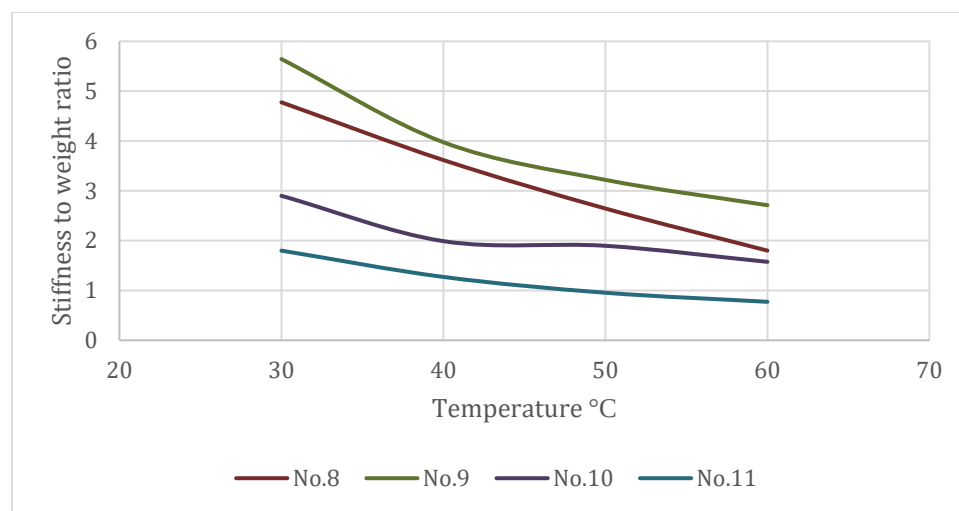
Model No.	Stiffness to weight ratio			
	Without effect of temp.	at 40°C	at 50°C	at 60°C
1	3.331	2.362	1.416	1.181
2	4	3.161	2.614	2.098
3	4.498	3.437	2.871	2.454
4	2.573	1.575	1.263	1.12
5	4.59	3.91	2.66	2.466
6	3.76	2.337	2.144	1.929
7	2.386	1.646	1.363	1.05
8	4.776	3.617	2.645	1.8
9	5.644	3.975	3.22	2.711
10	2.9	1.99	1.897	1.575
11	1.8	1.272	0.955	0.773

Table 8. The effect of temperature on the stiffness to weight ratio of fins reinforced with carbon fibres

Model No.	Stiffness to weight ratio			
	Without effect of temp.	at 40°C	at 50°C	at 60°C
12	5.196	4.282	2.8	2.509
13	5.263	3.461	2.694	2.021
14	5.278	2.764	2.124	1.63
15	4.2	2.634	1.868	1.453
16	9.35	5.769	4.671	3.175
17	4.55	3.701	3.09	2.087
18	3.477	2.026	1.555	1.346
19	8.549	7.511	5.13	3.42
20	4.176	2.635	1.977	1.393
21	4.377	2.253	1.662	1.02
22	2.869	1.9	1.488	0.86



70% polyester 60% polyester



50% polyester

Figure 9. The effect of temperature on the stiffness to weight ratio of rocket fins reinforced with chopped glass fibres

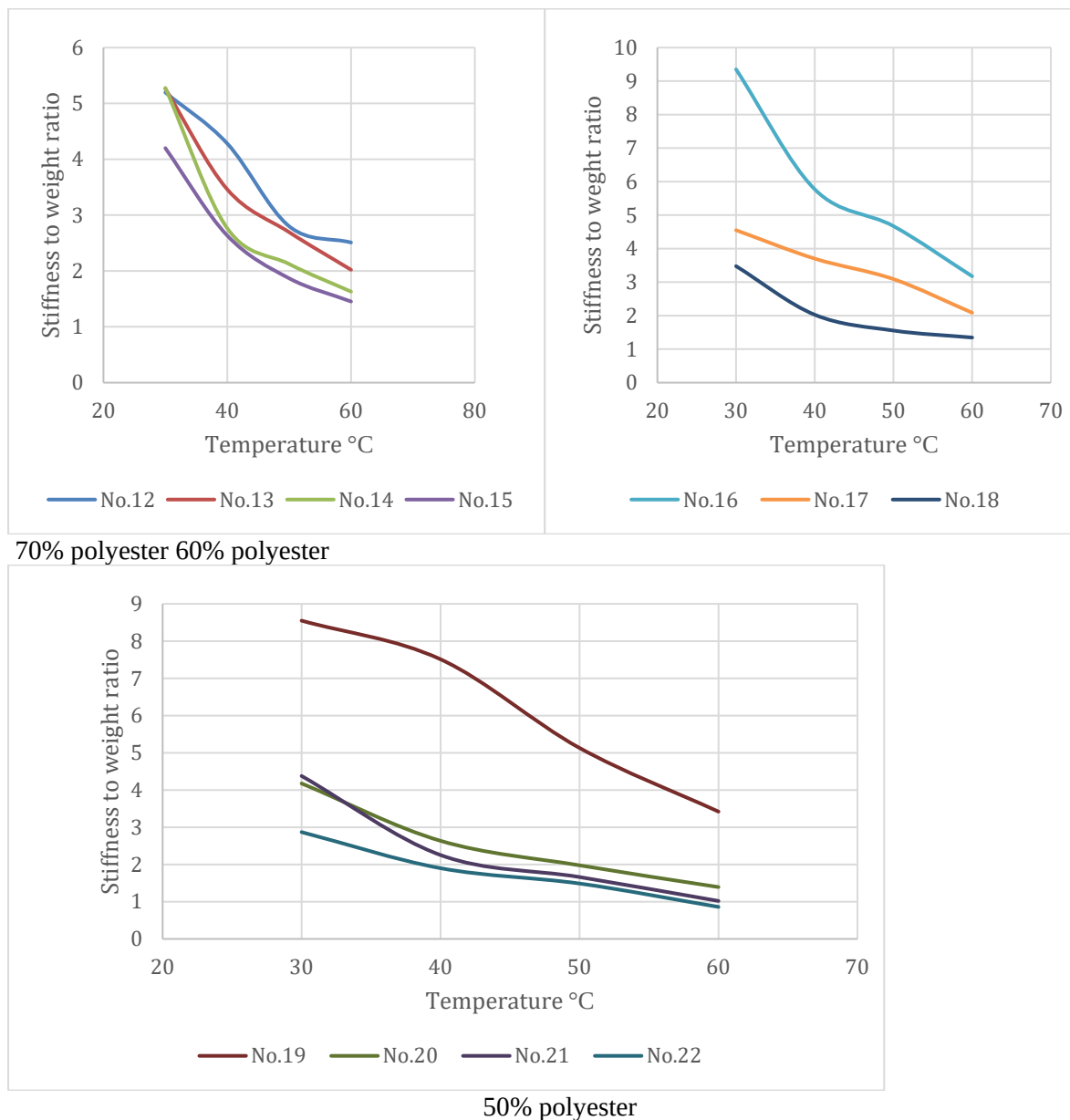


Figure 10. The effect of temperature on the stiffness to weight ratio of rocket fins reinforced with chopped carbon fibres.

5. Conclusions

Increasing the volume fraction of the carbon powder leads to a decrease in the maximum deflection of the fin, which leads to an increase in the stiffness to weight ratio of the material used. The largest percentage of improvement in the value of stiffness for the models reinforced using glass fibres was 69.87%, which occurred in model no.9 (50% polyester, 30% glass fibres, and 20% carbon powder), while for the models reinforced with carbon fibres, it was 79.94% and occurred in model no.16 (60% polyester, 30% carbon fibres, and 10% carbon powder). In addition, the results showed that increasing in the temperature led to a decrease in the stiffness to weight ratio for all models. The smallest effect of temperature on the stiffness to weight ratio for the models reinforced with chopped glass fibres was shown in model no.10 (50% polyester, 30% glass fibres, and 20% carbon powder) at 45.83%, while the lowest effect for models reinforced with carbon fibre occurred in model no.17 (60% polyester, 20% carbon fibres, and 20% carbon powder) at 57.54%.

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