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Thermal and Static Properties Investigation of Different Intake Manifold Materials to Lower Air Intake Temperature for Improved Engine Performance

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ABSTRACT

Formula SAE competition is targeted at students who are interested in designing and developing a Formula-type race car. Rules were imposed to restrict the car's performance for safety besides encouraging problem-solving skills. One such rule is the requirement of a 20mm restrictor inserted between the carburettor and intake manifold to reduce the air intake. With a constricted airflow creating a bottleneck effect, less air will be provided to the engine for combustion, consequently reducing engine efficiency. The purpose of this project is to overcome this problem despite the restriction imposed by the rules. This is done by choosing an intake manifold material that provides a low air temperature while withstanding the stress and vibrations from the engine. Computational Fluid Dynamics (CFD) software was used to conduct the static, thermal and modal analysis of Aluminium Alloy 6063, Gray Cast Iron, Fibreglass Epoxy and Carbon Fibre Epoxy to choose the material that produces lower intake air temperature while maintaining high strength. Carbon fibre epoxy was found to provide the best durability against static stress while maintaining a lower intake air temperature compared to the other materials tested.

1. Introduction

A Formula SAE car is a lightweight, low-velocity racing car that is used during an SAE competition to test the car's performance as well as technical inspections, among other criteria [1]. The cars are fully developed by the students involving methods such as designing and analyzing the chassis [2, 3] and designing the crash attenuator for reducing impact during collision [4]. Engine performance was also refined by redesigning the operative inlet for a better air-fuel mixture in the engine [5] and performing diagnostics remotely using applying Internet of Things (IoT) [6–13]. Intake manifold is a part of the engine located between the engine cylinder and throttle body. The primary function is to provide uniform air and fuel mixture distribution to all cylinder runners by splitting the amount of air

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sucked into the engine cylinder. Essentially, uniform distribution of air is crucial to provide better performance and ensure optimum efficiency of the engine, as it is the main function of the intake manifold [14].

The input air is given by the intake manifold to the engine is important since the output power mainly depends on the input. The parameters studied for a higher intake were size, shape, material, and manufacturing [15, 16]. Decreasing the air temperature has shown to increase the density which ultimately increases the volumetric efficiency [17].

Heat transfer on solid surfaces depends on several factors which include the material thermal properties, surface roughness and interface temperature. From engine tests that had been conducted, it was concluded that manifold temperature did not exceed 100˚C despite withstanding exhaust gas recirculation of 430˚C temperature [18]. The ability of an intake manifold to withstand high temperatures plays a vital role in its longevity as the thermal load is known to reduce stiffness and strength which are crucial for structural performance [19]. The knowledge obtained from the literature review is summarized in Table 1 along with a few hypotheses that form the foundation of this study.

Table 1
Literature review summary

No	Findings	Reference
1.	Intake manifold temperature does not exceed 100˚C	[18]
2.	Power output of an engine is directly related to air intake temperature and pressure	[20–24]
3.	Lower intake air temperature exhibits improvement in fuel consumption and exhaust emissions	[14], [25–28]
4.	High thermal load reduces structural performance and integrity	[19], [29–34]
5.	Pressure load is a critical criterion for simulating structural load in an automobile manifold analysis.	[35–37]
6.	Modal analysis frequency is important for predicting and assessing the dynamics of design and material proposal.	[32],[35] [38–40]
7.	A higher natural frequency is needed in avoiding structural failure caused by resonance	[29–31], [39], [41]

In conclusion, the selection of intake manifold focuses on lowering the temperature which will consequently improve the efficiency of the engine output and fuel consumption. However, the structural integrity is prioritized for the safe operation of the intake manifold under harsh conditions of consistently high temperature and pressure.

2. Methodology

Design analysis is conducted through simulation. The software used for the analysis is licensed Ansys 2021 R2. The analysis procedure consists of thermal, static, and modal analyses. The results for all considered materials will be compared and discussed afterwards. The materials are chosen by considering the thermal and stress conditions [35, 42, 43]. Commonly used materials for intake manifolds such as aluminium and cast iron are also included in the study. The mechanical and thermal properties of the considered materials are shown in Table 2.

Table 2
Properties of materials considered for the analysis [35, 37]

Material	Mechanical Properties
Aluminium Alloy 6063	Density, ρ: 2770 kg/m3
	Tensile Yield Strength: 280 MPa
	Tensile Ultimate Strength: 310 MPa
	Thermal Conductivity, λ: 200 W/(m·K))
	Specific heat, Cp: 875 J/kg K
Gray Cast Iron	Density, ρ: 7220 kg/m^3
	Tensile Yield Strength: 3220 MPa
	Tensile Ultimate Strength: 2440 MPa
	Thermal Conductivity, λ: 52 W/(m·K)
	Specific heat, Cp: 447 J/g K
Fibreglass Epoxy	Density, ρ: 1850 kg/cm3
	Tensile X Direction: 0.78 GPa
	Tensile Y Direction: 0.031 GPa
	Tensile Z Direction: 0.031 GPa
	Thermal conductivity, λ: 0.4306 W/(m·K)
	Specific heat, Cp: 700 J/kg K
Carbon Fibre Epoxy	Density, ρ: 1800 kg/m^3
	Tensile Yield Strength: 3220 MPa
	Tensile Ultimate Strength: 3584 MPa
	Thermal Conductivity, λ: 6 W/(m·K)
	Specific heat, Cp: 800 J/g K

2.1 Transient Thermal Analysis

Table 3 shows the boundary conditions that are used for the thermal analysis. The thermal loads applied are the incoming hot air from the carburetor and the outlet which reached the following temperature from the engine while the body is exposed to heat from the surroundings. The values for engine backflow heat flux and conduction were obtained from similar research [18, 44]. The temperatures of the intake manifold, the air inside, and the heat flux were recorded for discussion.

Table 3
Thermal Analysis Boundary Conditions [18, 44]

Boundary Conditions		
Initial Temperature	Initial Temperature Value	26 ˚C
Convection	Geometry	Body
	Film Coefficient	15 W/m^2 ˚C
	Ambient Temperature	50˚C
Heat Flux	Geometry	Outlet
	Magnitude	3.e-005 W/mm^2
Temperature	Geometry	Inlet
	Magnitude	45˚C
Temperature 2	Geometry	Outlet
	Magnitude	90˚C

2.2 Static Analysis

The pressure values used in the boundary conditions shown in Table 4 are obtained from the reading of the Suzuki GSX-R 600 2005 engine model using Haltech Engine Management ECU Software [45]. The pressure is recorded when the engine is at an idle speed of 3300RPM which resulted in the total pressure at the inlet to be equal to the ambient pressure of 101325 Pa. The data of stress, strain and deformation towards the intake manifold were generated. The whole process is illustrated in Figure 1 below.

Table 4
Static Analysis Boundary Conditions [45]

Boundary Conditions		
Pressure 1	Location	Inlet
	Relative Pressure	101325 Pa
Pressure 2	Location	Outlet
	Relative Pressure	59025 Pa
Fixed Support	Location	Inlet and all outlets

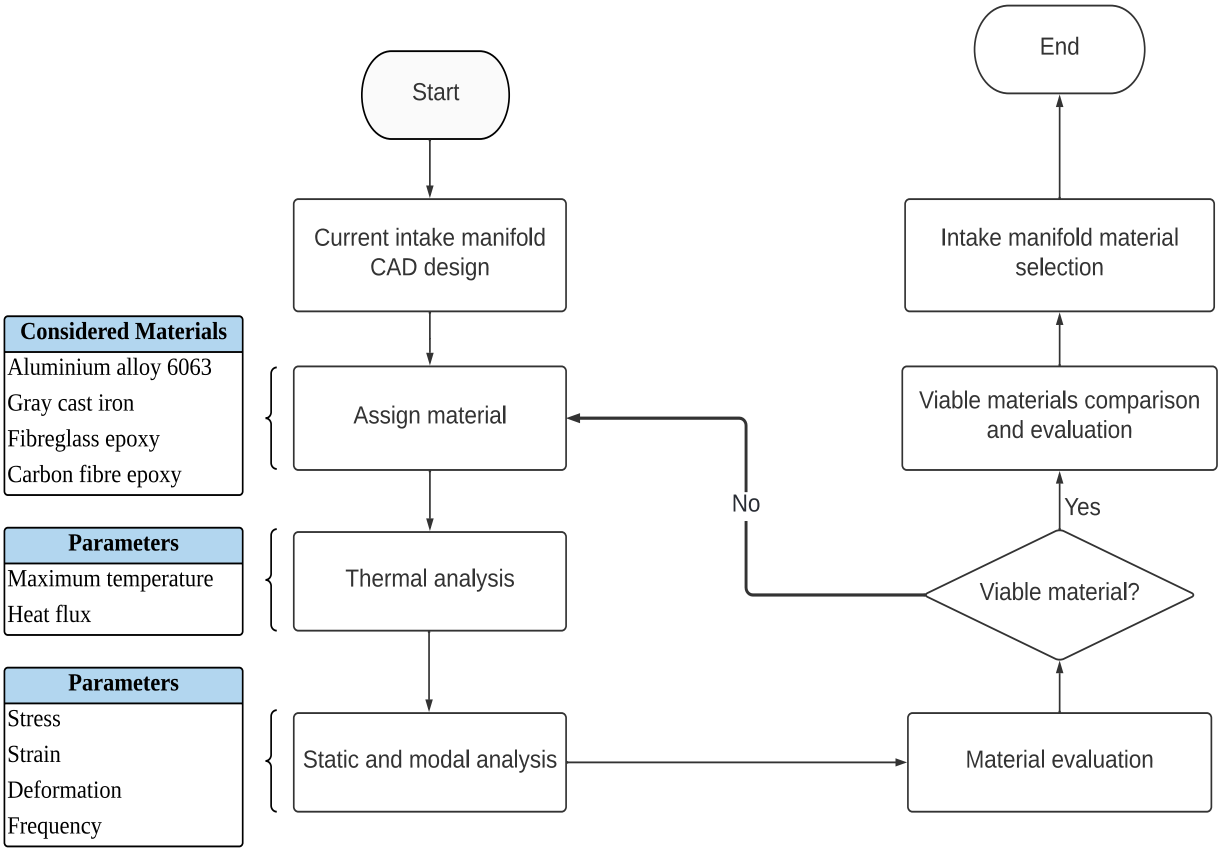

Fig. 1. Methodology flowchart

3. Results and Discussions

The simulation results based on the procedure are shown and discussed. The results are based on the constraints that have been taken into consideration while conducting the research. The results for each analysis are separated into their respective subcategories and will be discussed accordingly for selection.

3.1 Thermal Analysis

Table 5 presents the results of applying thermal load to all the materials being considered. The highest thermal load from engine conduction at the intake manifold base resulted in the highest heat source towards the intake manifold temperature. Aluminium alloy may have higher heat capacity, but it has a high thermal conductivity as well as low density. This resulted in significant heat absorption by the material, causing it to achieve the highest temperature. Theoretically, polymer matrix composite materials, or epoxy composites, conduct less heat than metals due to their low thermal conductivity. This explains why fibreglass yielded significantly low values in all categories. However, carbon fibre is an exception since the temperature is slightly higher than grey cast iron and significantly higher than fibreglass. This is due to the organization and structure of fibres in the epoxy which influence the contact resistance [46].

Thermal conductivity and porosity are influenced by the contact resistance, which leads to a higher temperature with the use of highly conductive carbon fibres in the epoxy. However, with the outer layer of epoxy covering the composite materials, the heat absorptivity is still lower than aluminium alloy. Despite having similar temperatures, the heat flux in grey cast iron is greater than in carbon fibre, which signifies a higher rate of thermal energy flowing. The presence of graphite in cast iron significantly affects the material's thermal conductivity, which leads to a higher heat flux. The high heat flux ultimately increased the air temperature to the point where it exceeded the manifold temperature.

Table 5
Thermal results of the analyzed intake manifold materials

Material	Manifold Temperature (˚C)		Air Temperature (˚C)		Heat Flux (W/mm^3)	
	Min	Max	Min	Max	Min (x10^{-6})	Max (x10^{-2})
Aluminum Alloy	44	90	44	99	7.5061	11.88
Gray Cast Iron	38	90	38	95	6.9823	6.3142
Carbon Fibre	39	90	39	90	0.2047	1.7951
Fibreglass	32	90	36	90	0.0552	0.4206

3.2 Static Analysis
3.2.1 Stress

Figure 2 depicts the stress on the intake manifold, with aluminium alloy experiencing the greatest stress. Thermal loads tend to physically alter the model through expansion or contraction, causing stiffness and strength reduction. Aluminium alloys are known to lose their strength when exposed to high temperatures and this lowers the resistance of the material against the load. The results had shown that aluminium experienced the highest temperature which correspondingly led it to obtain the highest stress, almost twofold those of grey cast iron. It was also stated by Emerson et. al that the material was shown to have lower performance than cast iron [47]. A material's density influences its strength as denser materials equal fewer voids and porosity in its structure [48]. The dense microstructure and compositions of grey cast iron enable it to withstand the load better than aluminium alloy. Fibre-reinforced composites are engineered to exhibit high fatigue resistance and strength-to-weight ratio, which is why carbon fibre and fibreglass epoxy experience lower stress levels. Carbon fibre is known to be a superior fibre reinforcement in terms of strength and stiffness due to the carbon microstructure. Although carbon fibre is weaker in handling compressive force, epoxy is strong in withstanding it.

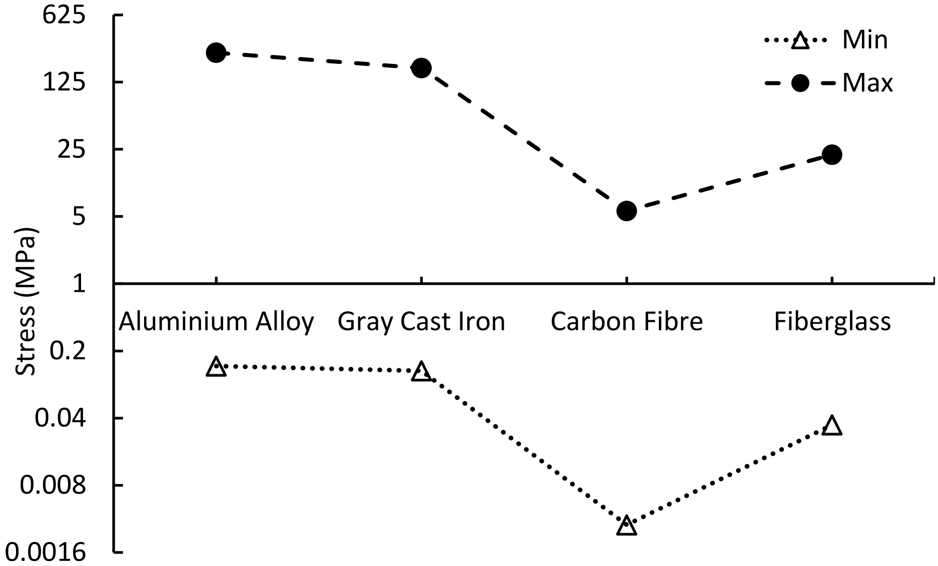

Fig. 2. Stress experienced by the intake manifold

3.2.2 Strain

The strain experienced by each material is illustrated in Figure 3. Composite materials such as carbon fibre and fibreglass epoxy showed high resistance against stress compared to metal. However, the largest value for minimum and maximum strain occurred in fibreglass. This poses a potential failure during operation since composite materials are most susceptible to failure when strained even by a small amount. Nevertheless, carbon fibre has higher tensile strength and elasticity which enables it to withstand strain to a higher degree. The strain experienced by the material is more appropriate for composite materials. However, previous study had shown that fibreglass is able to withstand more strain and deformation than carbon fibre prior to failure [49]. Aluminium alloy experienced a relatively high amount of strain due to its low yield strength. On the other hand, grey cast iron exhibited a similar high strain due to its density, albeit at a slightly lower level due to its much higher yield strength.

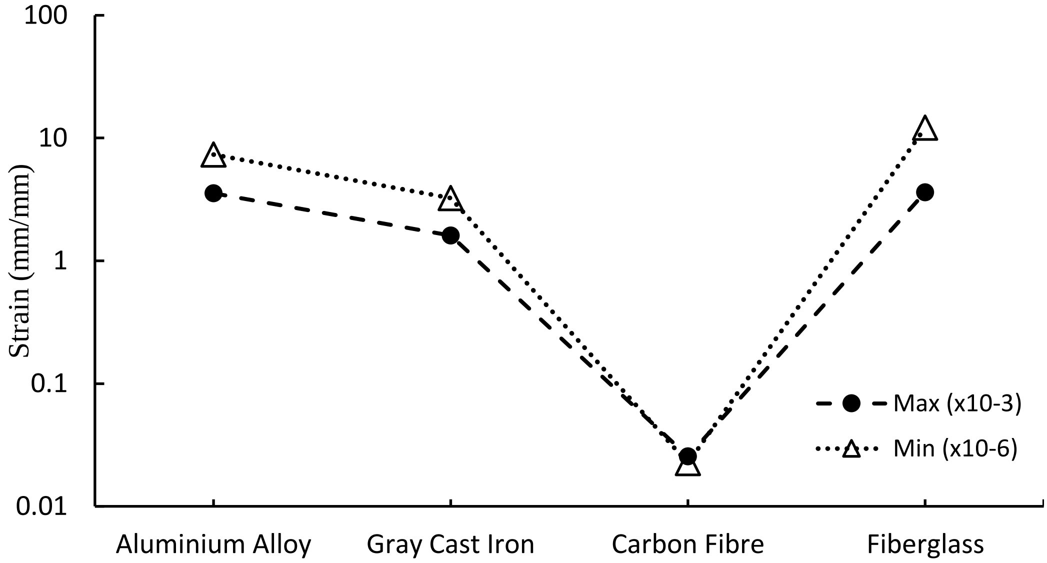

Fig. 3. Strain experienced by intake manifold

3.2.3 Deformation

Figure 4 shows the deformation that occurs in the intake manifold for each material. Each material has different expansion and contraction rates resulting from the static and thermal load. The intake manifold, which is sealed to a gasket towards the engine metal cylinders, must have a minimal expansion to reduce pulling and twisting forces towards the gasket, otherwise, leaks and eventually cracks will occur.

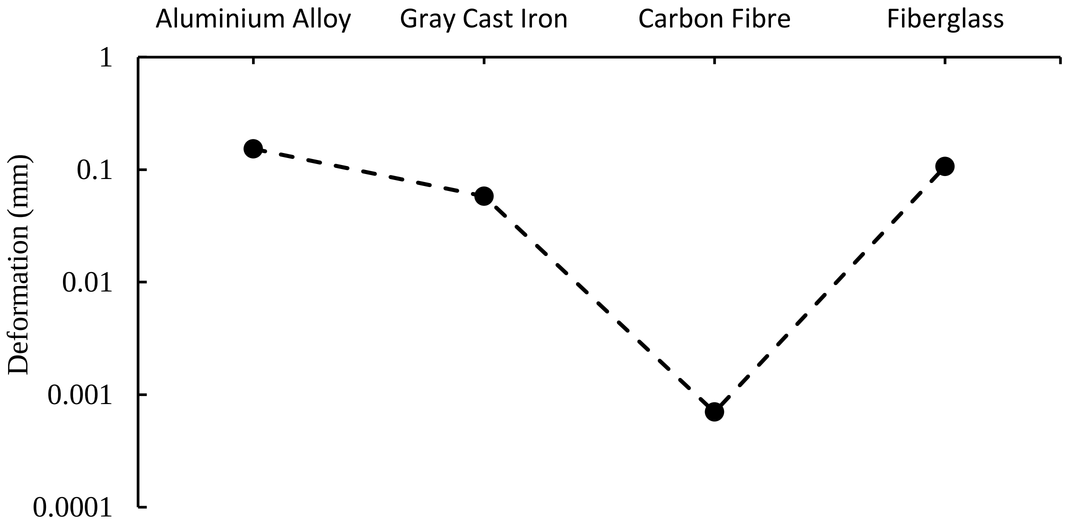

Fig. 4. Deformation experienced by intake manifold

Aluminium alloy has the highest thermal expansion coefficient among the compared materials, resulting in the highest deformation when combined with a large amount of stress. Grey cast iron performed better than aluminium alloy, as expected by observing the results of experiments conducted by other researchers [31, 50] and had also outdone fibreglass in withstanding strain and deformation, despite experiencing a large amount of stress that is almost 8 times larger than fibreglass.

This is due to the grey cast iron microstructure and compositions that contain carbon which causes the material to become brittle and perform better under compressive loads [46]. Polymer matrix composite materials are more flexible but are more prone to damage. Strong covalent bonds form the layers of the fibres, giving them a brittle property that allows cracks to propagate even under minor strain and coalesce into failure [51].

This explains the high deformation that occurs in fibreglass as the material experiences the highest strain. Increasing the composite volume can improve the mechanical properties of the material. However, there are still some properties that are considered subpar when compared to metals. Despite being a polymer matrix composite material, carbon fibre had experienced an infinitesimally small strain which leads to a micro-scale of deformation. This is due to the material's strength and ability to withstand deformation and expansion from both structural and thermal stress.

3.3 Modal Analysis

A total of 5 modes were generated from the simulation and will be discussed according to the subcategory of frequency and deformation.

3.3.1 Frequency

Figure 5 shows the natural frequency the material experienced in each mode. A softer or pliable material with a high damping coefficient reduces the natural frequency. However, high temperatures can also decrease natural frequencies. Due to the soft and flexible nature of fibreglass epoxy, it has obtained a remarkably low natural frequency throughout all 5 modes. Grey cast iron is known for its excellent damping capability due to the presence of cementite in its composition which is able to reduce noise and vibration, which results in a lower natural frequency. The stiffness of carbon fibre had caused its natural frequency to become significantly high and continuously increasing.

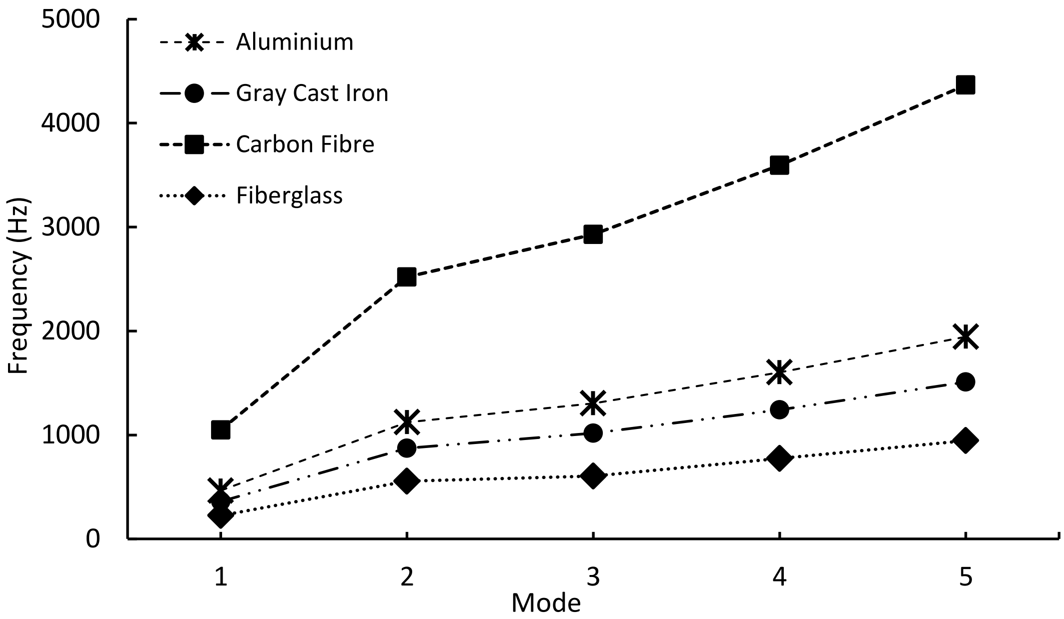

Fig. 5. Natural Frequency for Intake Manifold

3.3.2 Deformation

Figure 6 illustrates the highest deformation occurring towards the intake manifold in each mode. A higher value of vibration mode does not necessarily mean higher maximum deformation as all the compared materials, except grey cast iron, have a higher deformation in Mode 3 than in Mode 4. The deformation that occurs is more sensitive toward energy dissipation rather than stiffness degradation, regardless of the mode order. However, the sensitivity increases as the mode order increases [52]. This is due to the strain energy increasing along with the mode order increment which consequently causes large deformation in composite materials despite having a lower frequency.

The presence of copper and silicon in the composition of the aluminium alloy decreases the deformation despite experiencing a relatively high amount of natural frequency. The high stiffness of Carbon Fibre has consequently caused the material to experience equally high deformation. Despite having the lowest natural frequency, Fibreglass obtained the largest deformation. The performance differences between these two composite materials are explained by Pedro [53], which is due to their strength and stiffness, with Carbon Fibre having superior strength and stiffness.

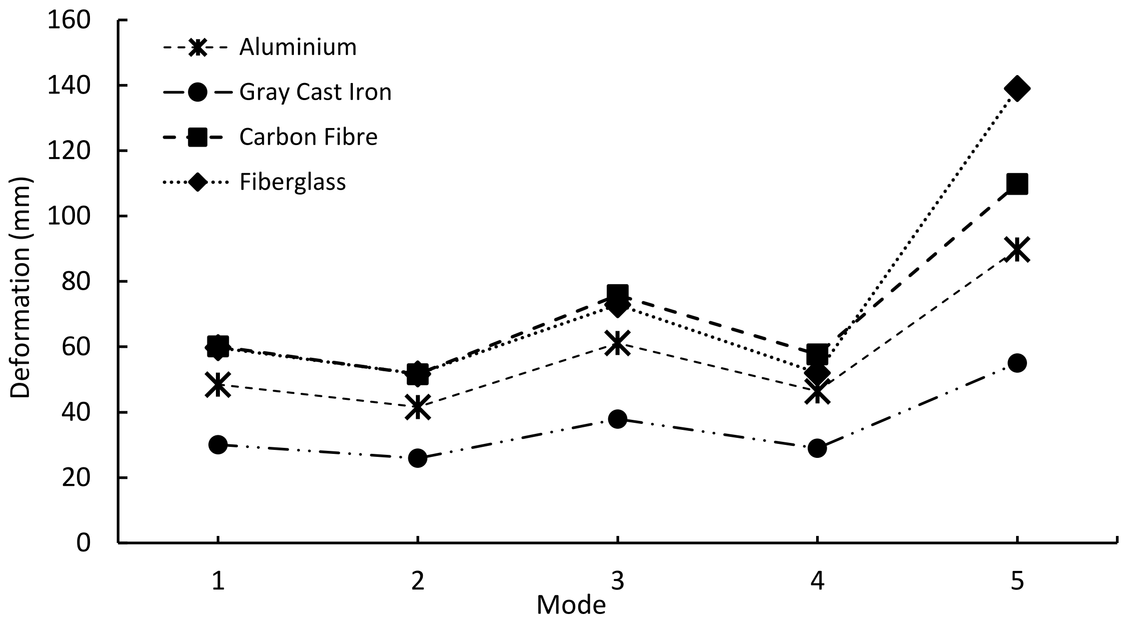

Fig. 6. Maximum Deformation for Intake Manifold

Since low air temperature is able to increase the engine's efficiency, the material selection should have the lowest thermal values. However, the intake manifold experiences a high amount of pressure and vibrations during operation. Hence, the material selection should be made not just based on the air temperature, but also based on its capability to withstand the static and dynamic load for the sake of smooth and safe operation. Fibreglass obtained the lowest temperature for both air and manifold by a large margin compared to other materials. However, its structural performances are below subpar and show borderline failure during operations. Therefore, the most balanced choice is Carbon Fibre since it provides a relatively low air temperature while being able to withstand the static and dynamic load. Hence, Carbon Fibre was selected for this study.

4. Conclusions

An investigation to analyze an appropriate material for the application of an intake manifold to an FSAE car has been presented. These were achieved by simulating the thermal and structural load to the intake manifold made of Aluminium Alloy 6063, Gray Cast Iron, Fibreglass Epoxy and Carbon Fibre Epoxy. The load values were obtained from similar studies that measured the load through experimental methods. Despite not excelling in each category, the selected material was chosen for its safety and superior performance in static and modal analysis.

Carbon fibre was selected as the material to be used due to its significant performance in strength and modal analysis while keeping a relatively low temperature for both air and manifold. Fibreglass was supposedly chosen as the new material due to its superior thermal properties, however, the strain experienced was too large which poses a risk of failure during operation since composite materials are highly sensitive to strains.

In conclusion, this study provided a feasible analysis to select a material for the application of an intake manifold towards an FSAE car. However, this study excluded the materials' physical properties such as the surface roughness. Correspondingly, future works need to involve thermal load due to friction, as well as airflow obstruction due to the material's surface roughness.

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