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Case Study

Structural Comparison of Naturally Aspirated and Turbocharged Diesel Engine for Steel and Aluminium Made Radiator: A Finite Element Study

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ABSTRACT

The current study is based on the structural analysis of radiators made of different materials to compare their effectiveness in the case of naturally aspirated and turbocharged diesel engines. For the analysis of the radiator structure, ABAQUS software was used. In the ABAQUS, static structural analysis was made to calculate the strength of the radiator. The said software is capable of calculating the strength of the radiator considering the boundary conditions (i.e., fixing at corners) as well as the loading conditions. It was observed that stresses generated while using an aluminium radiator were very high than those produced by steel radiators. According to the study, the following are the key findings for the steel and aluminium radiators. In the first case, while three corners were fixed, the steel radiator showed a deflection of 1.86 mm while aluminium exhibited 5.65 mm. However, in the second case in which the radiator had four fixed corners, the deflection of the steel radiator was 1.10 mm, while that of aluminium was 3.36 mm. Additionally, based on the deflections obtained from all investigations, it was found that radiators made of aluminium were more sensitive than those made of steel in both naturally aspirated and turbocharged applications. However, due to aluminium's strong thermal conductivity, it is compatible with naturally aspirated engines in terms of thermal capacity. To combat turbocharged engine complications caused by high

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temperatures, such as thermal cracking, engine wear and tear, and so on, a steel-made radiator is more suitable than an aluminium radiator, hence mitigating the issues.

Keywords: Aluminium radiator, naturally aspirated, steel radiator, structural analysis, turbocharged

INTRODUCTION

Engine cooling is critical for maintaining the engine's optimal operating temperature for the vehicle's speed and road conditions (Roy et al., 2017a). When engines are driven at high rpm to increase the vehicle's speed, the heat in the engine's components increases dramatically (Sharma et al., 2022). Therefore, it is critical to lower the temperature of a vehicle's internal combustion engine (ICE) by collecting heat and dissipating it into the air. The engine will work optimally with a properly functioning radiator (Habeeb et al., 2020). The radiator is an integral component of the engine cooling system (Wani et al., 2019). It is a heat-type transfer fluid that removes excess heat generated by combustion engines (Elias et al., 2019). Due to rising values of forced convection within radiators, the heat transfer capacity and convective heat transfer coefficient across the radiator rise with increasing water intake velocity and mass flow rate (Dalkilic et al., 2019). Now, a common practice in the manufacture of radiators for automobiles is the use of lightweight materials. Typically, such a structure is constructed of copper and aluminium alloys that are employed as a cooling mechanism for the vehicle engine due to their stainless nature and superior corrosion resistance over iron alloys (Chahardoli et al., 2021).

In recent times, the automobile industry has been striving towards manufacturing components that are smaller in size and lighter in weight for improved fuel efficiency (Zainy, 2021). lightweight design has attracted extensive attention in the automobile industry to reduce energy consumption and emissions, and decision-making requires a thorough examination of materials, structures, manufacturing, recyclability, and economics (Chu et al., 2019). Furthermore, continuous advancements in manufacturing technology, materials science, and distribution enable the incorporation of novel manufacturing methods and materials into production processes. Radiators are an example of such a product, as they may be made from a variety of materials (cast irons, steels, bronzes, and aluminium alloys) and manufacturing procedures (Pańcikiewicz & Radomski, 2020).

Researchers are continually working to improve the cooling performance of car engine radiators to achieve sustainable and efficient resource utilisation. Throughout this exercise, appropriate material, efficient tube design, and coolant contribute significantly to improving heat exchange and thus radiator efficiency (Arora & Gupta, 2020). Aluminium has recently gained popularity because of the aviation and car sectors' need for lightweight components. These have been utilised to create lightweight transmission cables, heat exchangers, evaporators, cylinder heads, and automobile radiators (Vijayakumar et al., 2020). However, aluminium radiators have the problem of being delicate, as aluminium is a soft metal in composition, making mechanical damage quite simple. Furthermore, the impact of these radiators on erosion is dependent on the pH of the water; this indicator should be in the range of 7–8 per cent since, at lower levels, this metal frequently fails, erosion occurs, and the radiator eventually fails (Mo'minov & O'tbosarov, 2021). Interestingly steel panel radiators are the most prevalent form of panel radiator used in homes, workplaces, and industrial locations and are typically supplied with natural convection shutters (convectors) to increase heat output (Gelis & Akyurek, 2021). Therefore, it is required to become as familiar with the material as possible to develop this work and to review a large amount of related literature and materials (Ondriga et al., 2021).

The total heat transfer coefficient and entropy generation from panel radiators were investigated, and radiator size increases with increasing flow rate and supply temperature; the total heat transfer coefficient decreases with increasing radiator size and temperature but increases with increasing flow rate (Gelis, 2021). In addition, the most often used radiator tubes have a linear structure and are supported by straight flat plates to offer additional strength to withstand the force of air acting on the tubes, which can cause them to fail (Aravindkumar et al., 2021). In general, in the case of radiators, optimising the temperature distribution on the heater's surface in order to produce the highest potential radiator heat output is vital, but it is only solved once during the radiator's construction (design) and strength of the material (Dzierzgowski, 2021).

Recently, emphasis has been placed on optimising cooling efficiency by introducing the thermophysical characteristics of the nanoparticles scattered in the base fluid, and nanofluids are utilised to improve heat transmission in the engine radiator (Ramalingam et al., 2020). Nanofluids have the potential to improve the thermophysical characteristics of heat transfer fluids. Thermal conductivity is critical in applications requiring quick heating and cooling (Ranganathan, 2019). Several failure possibilities include oil leaking at the contact between the radiator element and the plug, element rupture, and plug separation from the bottom opening. The major failure mode is radiator element cracking (Timelli et al., 2019). The finite element model incorporates the stiffness of the entire radiator assembly to accurately simulate the radiator's physical behaviour (Roy et al., 2017b). Different load variations and material changes are utilised to research and suggest a suitable material to sustain structural and dynamic stresses (Gudimetla et al., 2012).

This study's specific objective is to compare the same design radiator made of different materials. For this purpose, radiators made of steel and radiator made of aluminium are selected and analysed with different load cases. Deflection plots, as well as stress plots, are created to compare different parameters of both radiators. Considering the temperature danger posed by turbocharged Diesel engines, a steel-made radiator was considered, and structural analysis was done. Similarly, an aluminium-made radiator was selected for naturally aspirated engines. The study's ultimate objective was to assess the structural strength of both materials.

MATERIALS AND METHODS

Aluminium and steel were chosen for their distinctive features while keeping in mind the factors contributing to the durability of both types of engines and their adequate cooling supply.

Aluminium is a light metal with a good thermal conductivity ($200W.m^{-1}.K^{-1}$). It has a low emissivity that cannot be increased via heat oxidation in the presence of oxygen. When pure aluminium is exposed to air, the aluminium atoms in the surface layer react rapidly with the oxygen in the air, forming a thin and robust Al_2O_3 oxide coating that protects the metal from further oxidation. Anodised coatings withstand temperatures of up to 300 °C and have at least five times the heat conductivity of black paints. In addition, anodising simplifies the process of obtaining a high emissivity. It makes aluminium a suitable material for compact, lightweight, portable radiators. Similarly, steel properties are formed by creating an invisible and adherent chromium-rich oxide coating. The protective Cr_2O_3 oxide layer forms on the stainless-steel surface at a rate proportional to the temperature, typically to a thickness of 1–3 nm. Due to their superior corrosion resistance, high-chromium austenitic stainless steels are in high demand for high-temperature applications (Bowler, 2016).

A model was designed to test the characteristics of different materials when applied to the same geometric design of the radiator. To do this, we built a middle surface model of the radiator with shell meshing on the surfaces, which enables us to perform finite element analysis on the radiator model.

Two distinct load conditions were applied to the steel radiator. In the first load condition, the model was fixed at all four corners, and a concentrated force was applied to the radiator model's centre. In the second load case type, the model was fixed at three corners and loaded at the fourth corner to determine the model's strength. As indicated previously, the same approach was used to create an aluminium radiator with the same design. Thus, we could compare the findings of the analyses performed on both materials and thus determine which one is stronger.

These are the following six steps involved in the execution of the project:

i. Geometry Preparation
ii. Middle Surface Generation
iii. Mesh Generation
iv. Analytical Model Preparation
v. Analysis
vi. Post Processing

Geometry Preparation

For the execution of this project, a suitable geometry of a sample radiator having a length and width of 485 mm and 347 mm, respectively, shown in Figure 1, was prepared. First, the geometric design of the radiator part was designed in the solid works software. Then the model was exported in IGS/STEP format to be readable in the pre-processing software for the analysis.

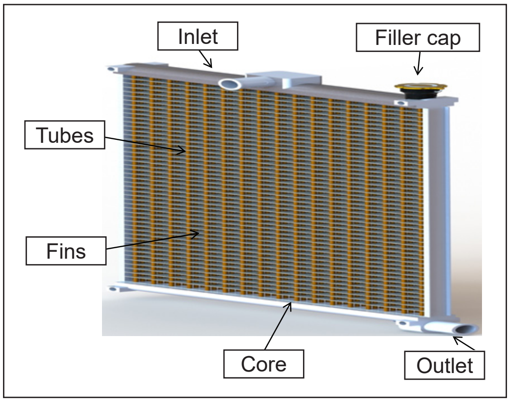


Figure 1. Radiator 3D model

Middle Surface Generation

The second phase was creating the centre skin for the available radiator design. First, all features, ribs, pipes, and walls had their middle surfaces constructed, and then an appropriate thickness of 19 mm at the walls and 47 mm at the corners was allocated to the corresponding middle surfaces. These centre surfaces were then linked to form the radiator's original component. Again, we utilised ANSA software for this purpose.

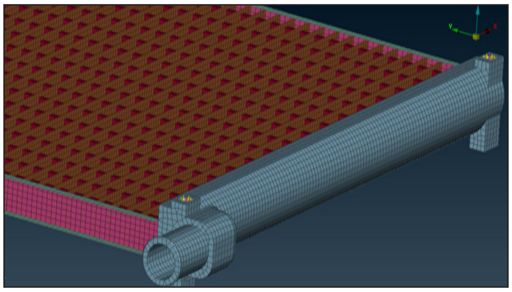


Figure 2. Mesh generation of the radiator

Mesh Generation

The third phase was critical, as it included meshing the centre surface portion with an average/density of 2.5 mm–3.0 mm in accordance with quality requirements, as illustrated in Figure 2. It is how we transformed our geometric model into finite elements. It enables us to define the analytical model before performing the finite element analysis. We performed all meshing operations in the ANSA programme, which served as a specialised pre-processor for analytical tasks.

Analytical Model Preparation

After meshing the geometric structure, an analytical model is defined for the analysis. For example, in Figure 2, all four corners of the radiator are fixed to the fixture positions, and a concentrated force of 1 kN is applied in the negative direction of the z-axis to the model's centre.

Analysis with Four Corners Fixed for Both Steel and Aluminium and Load Applied on Center (Load Case 1)

Boundary Conditions. The first load case fixed the radiator model from all four corners. Then, a concentrated load of 1 kN was applied to the radiator's centre to determine the strength of the steel and aluminium radiator, as shown in Figure 3.

Analysis with Three Corners Fixed for Both Steel and Aluminium (Load Case 2)

Boundary Conditions. In this case, the model was fixed at three corners, and a concentrated load of 40 N was applied to the fourth corner to determine the strength of the aluminium and steel radiator, as shown in Figure 4.

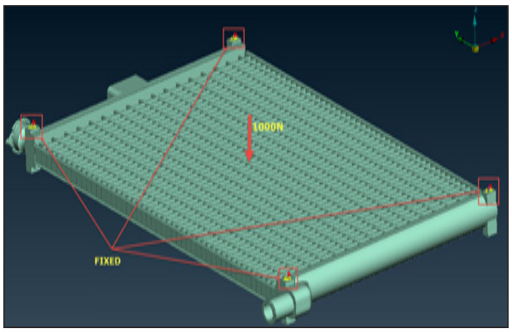


Figure 3. Analytical model for first boundary condition (Load Case 1)

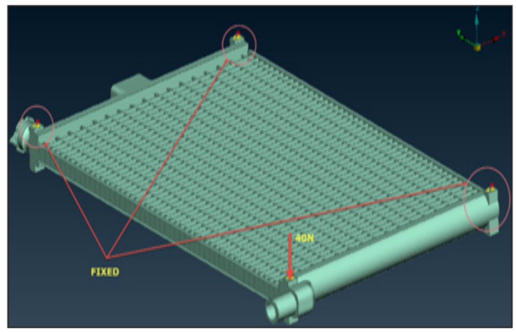


Figure 4. Analytical model for second boundary condition (Load Case 2)

Analysis

The radiator structure was analysed using the ABAQUS software. First, the strength of the radiator was determined using ABAQUS's static structural analysis. The software can calculate the radiator's strength while considering the radiator's boundary conditions (i.e., corner fixings) and loading circumstances. Two specific load cases were analysed: one with all four corners fixed and one with three corners fixed. Both types of analysis were carried out on the steel and aluminium radiators.

Post Processing

After running the analysis, results are extracted from the results file generated by the ABAQUS software. With the help of the result file, deformation and stress plots are generated, as discussed in detail below.

Materials Properties

The analyses were conducted utilising standard material data for both steel and aluminium. The standard values for each material are summarised in Tables 1 and 2.

Table 1
Materials properties of steel and aluminium

Material	Young's Modulus of Elasticity (MPa)	Poisson's Ratio	Density (tonne/mm^3)
Steel S235JR	210000	0.3	7.85E-9
Aluminium 1100	70000	0.33	2.7E-9

Table 2
Yield and tensile strength of steel and aluminium

Material	Yield Strength (MPa)	Tensile Strength (MPa)
Steel	235	360-510
Aluminium 1100	105	110

RESULTS AND DISCUSSION

The following sections discuss the analysis of steel and aluminium radiator load cases in detail.:

Steel Radiator Analysis with Four Corners Fixed (Load Case 1)

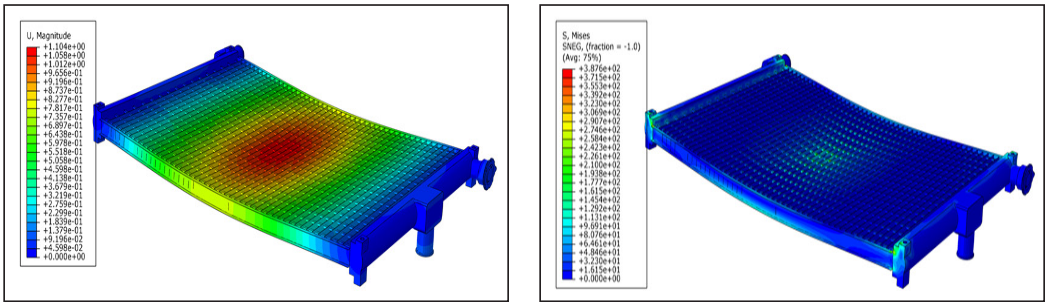
In the first load case, the radiator model was fixed from all four corners, and a concentrated force was applied to the radiator's centre to determine its strength. Additionally, demonstrate the Von Mises Stress distribution trend across the radiator, with a maximum resulting stress of 387 MPa, as shown in Figure 5.

It represents one of the critical areas of the part. We have very few areas where the stresses are just above the steel yield strength. It also represents the third corner, where we have almost all the fine stresses except the encircled ones.

Aluminium Radiator Analysis with Four Corners Fixed (Load Case 1)

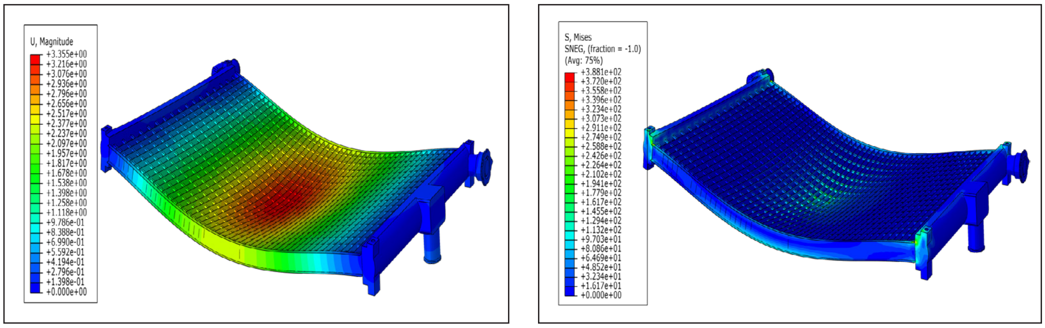
Similarly, the model was fixed from all four corners for aluminium-made radiators. A concentrated load of 1 kN was applied to the radiator's centre to determine its strength, as shown in Figure 6.

Following is the resulted deflection plot when the analysis was executed, on the radiator made of aluminium, according to the load case. The maximum deflection was found to be 3.36 mm, which is a much bigger deflection than the radiator made of steel. Also, it has shown the trend of Von Misses Stress distribution throughout the radiator made of aluminium with a maximum resulting in the stress of 388 MPa, which is very high



(a) (b)

Figure 5. (a) Deflection and (b) stress distribution plot for steel in load case 1



(a) (b)

Figure 6. (a) Deflection and (b) stress distribution plot for aluminium in load case 1

considering the strength values of aluminium. Furthermore, it also shows the Von Misses Stress distribution trend throughout the radiator with a three-colour legend maximised at 110 MPa. It is done for a clear understanding of the stress distribution with respect to the yield strength of the aluminium.

Stress Distribution (Load Case 2)

Figure 7 illustrates the stress distribution at the radiator's first critical corner for load case 1. because the stresses are significantly less than the yield strength, steel radiator components will not permanently fail or deform in these regions. Also, the Von Mises Stress distribution across the radiator is set to 235 MPa in the colour legend. It is done to ensure a complete understanding of the stress distribution in relation to the steel yield strength, as shown in Figure 8.

The stress distribution at the radiator's first critical corner is depicted in Figure 9 for load case 2. Since the stresses are significantly less than the yield strength, steel radiator components will not permanently fail or deform in these places. However, the stress distribution at the radiator's second critical corner is the point at which the aluminium component may break or deform permanently. Since the stress is substantially more than aluminium's yield and tensile strengths, as seen in Figure 10.

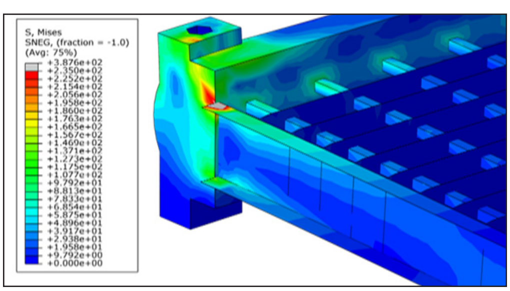


Figure 7. Stress distribution at the critical corners of the radiator for load case 1

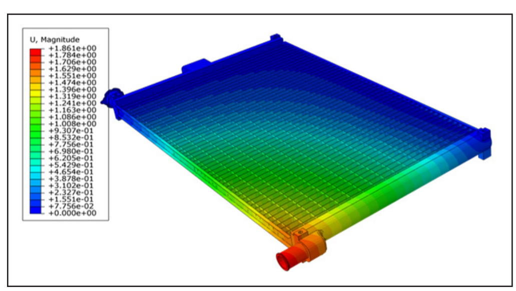


Figure 8. Von Mises Stress distribution throughout the steel radiator

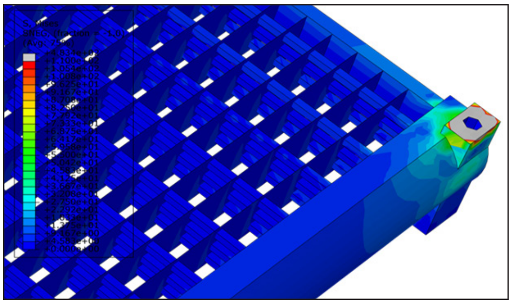


Figure 9. Stress distribution at the first critical corner of the radiator for load case 2

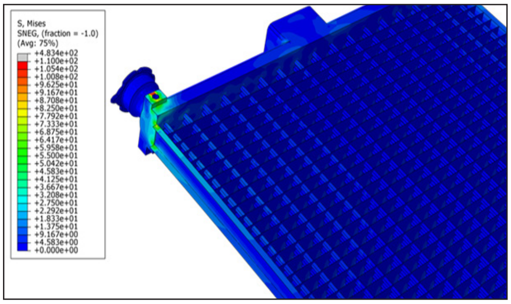


Figure 10. Stress distribution at the second critical corner of the radiator for load case 2

Graphical Stress Results Comparison

This graph compares the deflection of aluminium and steel for load case 1, in which a 1 kN force was applied at the centre, and the four corners were fixed. As seen in Figure 11, the resultant deflection is 1.104 mm for steel and 3.36 mm for aluminium, nearly three times the deflection for steel.

Similarly, the deflection of aluminium and steel for load case 2, which comprised a 40 N load applied at the corner while three corners were fixed, is shown in this graph. As seen in Figure 12, the resultant deflection is 1.86 mm for steel and 5.652 mm for aluminium, nearly three times the deflection for steel.

Moreover, the yield strength, ultimate tensile strength, and strain generated in steel and aluminium are also shown in the graphs below in Figures 13 and 14, when a 1 kN load is applied centrally. Four corners are fixed, three corners are fixed, and a 40 N load is applied to one end, referred to as case 1 and case 3, respectively. It is worth mentioning that aluminium's yield strength and ultimate tensile strength are quite low when compared to steel. In our analysis, we observed that the strains generated by an aluminium radiator

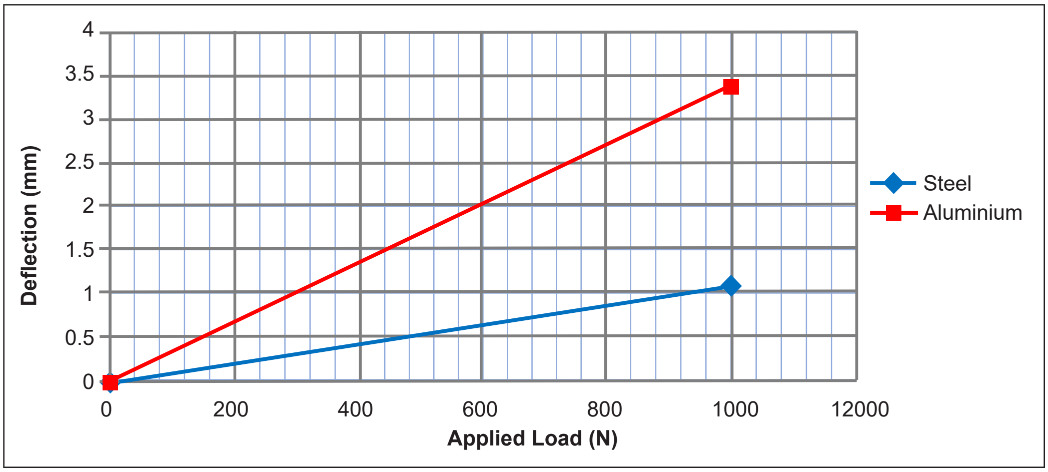


Figure 11. Deflection comparison for both aluminium and steel for load case 1

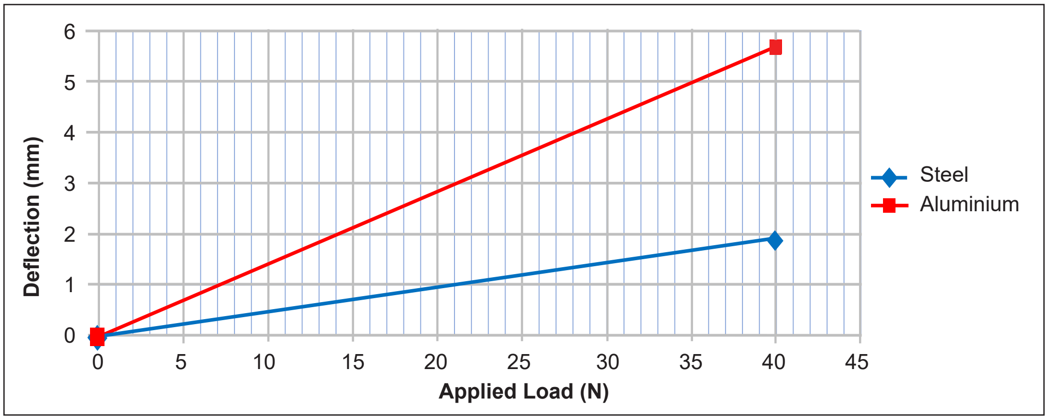


Figure 12. Deflection comparison for both aluminium and steel for load case 2

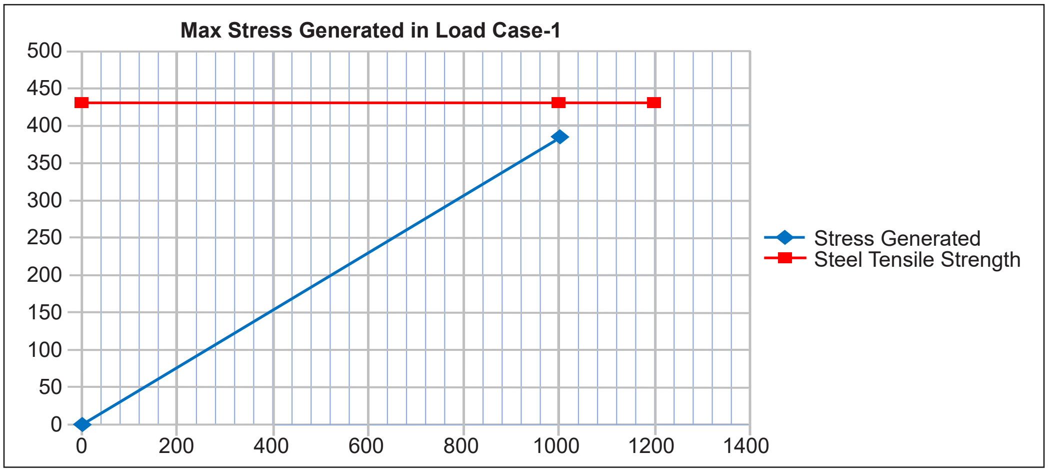


Figure 13. Steel maximum stress generated load case 1

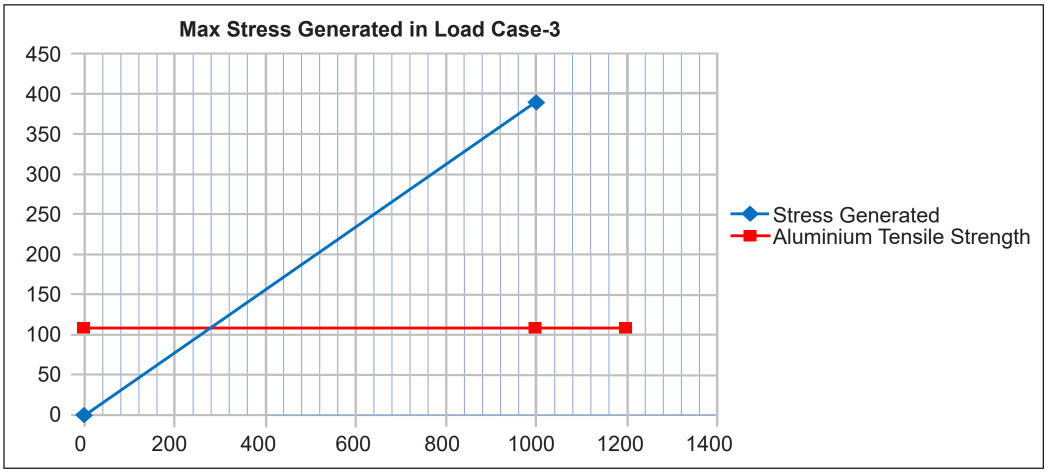


Figure 14. Aluminium maximum stress generated load case 3

were quite high in comparison to their strength. In contrast, the stresses generated by a steel radiator were relatively low.

Looking at the deflections obtained from all analyses, it is evident that the radiator made of steel is more durable than the radiator made of aluminium.

CONCLUSION

The current study mainly focused on comparing the radiator made of steel and the radiator made of aluminium. The yield strength and ultimate tensile strength of aluminium are low compared to steel's strengths. The radiator made of aluminium material was more sensitive compared to its counterpart material, i.e., steel, in both naturally aspirated as well as in turbocharged cases, as shown from the resulting deflections of the analyses. An aluminium-made radiator is compatible with a naturally aspirated engine as far as thermal capacity is concerned, owing to its high thermal conductivity. On the other hand, a steel-made radiator is more compatible with overcoming the turbocharger engine problems due to high temperatures, such as thermal cracking, engine wear, and tear, compared to its counterpart radiator to reduce the said problems. Structural analysis was carried out using a structural load of 1000 N (load case 1) in the centre and 40 N (load Case) in one corner to estimate the Von Mises stresses, strain, displacement, and deformation**.**

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