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Thermal and Structural Analyses of a Locally Developed Internal Combustion (IC) Engine Cylinder Head Using Finite Element Analysis (FEA)

[1]Oghoghorie, O., [2]Ebhojiaye, R.S. and [3]Amiolemhen, P. E.

[1]Department of Mechanical Engineering, Benson Idahosa University, Benin City
[2,3]Department of Production Engineering, University of Benin, Benin City
Email: ooghoghorie@biu.edu.ng; raphael.ebhojiaye@uniben.edu

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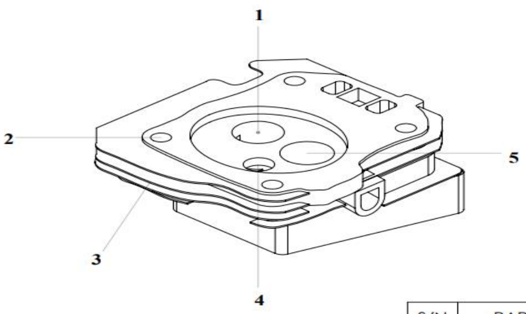
Abstract

This paper presents thermal and structural analyses of a locally developed cylinder head using Finite Element Analysis (FEA). A composite material that comprises coconut shell charcoal (CSC) and cow bone ash (CBA) as reinforcements and aluminium scraps as the matrix element was used to develop the cylinder head of a 4-stroke (107cc) IC engine. The cylinder head for the 107cc 4-stroke IC engine block was modelled using SOLIDWORKS software. Design of experiment was done using D-Optimal Mixture Design. The composite was prepared based on the different percentage by ratio of coconut shell charcoal, cow bone ash and aluminium matrix as obtained from the design expert system. Stir casting method was used for the casting process. The following results were obtained from the analysis. Temperature distribution was 200.000^{0}C maximum and 19.595^{0}C minimum, Total heat flux was 9.821 x 10^6 W/m^2 maximum and 96.969 x 10^{-4} W/m^{2}minimum, Equivalent (Von Mises) stress was 6.650 x 10^8 Pa maximum and 1.384 Pa minimum, Equivalent elastic strain was 9.521 x 10^{-3} maximum and 2.601 x 10^{-11}minimum, Total deformation was 2.557 x 10^{-4} m maximum and 0.000m minimum, Fatigue damage was 250.000 maximum and 250.000 minimum, Fatigue life was 1.000 x 10^8 maximum and 1.000 x 10^8 minimum and Fatigue safety was 15.000 maximum and 1.275 minimum. The results obtained were satisfactory when compared with existing literature.

1. Introduction

The understanding of new technologies in the development of engine components for internal combustion engine such as the cylinder head using a material with good mechanical and physical properties such as good wear resistance, corrosion resistance, light weight, high temperature etc, which is also cost effective and durable are the desires of a design engineers. In this research, a cylinder head of a 4-stroke IC engine was developed using a composite material that comprises coconut shell charcoal (CSC) and cow bone ash (CBA) as reinforcements and aluminium alloy from aluminium scraps as the matrix element. Design of experiment was done using D-Optimal Mixture Design. A three variable mixture design was used to design the experimental plan for this work. This is the most suitable experimental design method for optimizing formulation processes in which the input factors are the components of the product being formulated [1]. The composite was prepared based on the different percentage by ratio of coconut shell charcoal, cow bone ash and aluminium matrix as obtained from the design expert system. Stir casting method was used for the casting process. The main purpose of cylinder head is to seal the working ends of the cylinder and not to permit entry and exit of the gasses on over-head valve engines. The inside cavity of head is called the combustion chamber into which the mixture is compressed for firing [2]. The study is aimed at the thermal and structural analyses of the locally developed cylinder head using Finite Element Analysis (FEA) ANSYS

Figure 1 shows the 3D model of cylinder head while figures 2a and 2b show the developed cylinder head



S/N	PART NAME
1	In-let port
2	Stud
3	Cooling fin
4	Spark plug port
5	Exhaust port

Figure 1: The 3D modelling of the IC Engine cylinder head

Figure 2a: The plan view of the cylinder head

Figure 2b: The bottom view of the cylinder head

2.0 Thermal Analysis

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are: The temperature distributions, the amount of heat lost or gained, Thermal gradients and Thermal fluxes. The software used for the thermal analysis (ANSYS) supports two types of thermal analysis (Transient and Steady state analysis). A transient thermal analysis determines the temperature distribution and other thermal quantities under conditions that vary over a period of time [3]. Thermal simulations play an important role in the design of many engineering applications, including internal combustion engines, turbines, heat exchangers, piping systems, and electronic components. In many cases, engineers follow a thermal analysis with a stress analysis to calculate thermal stresses (that is, stresses caused by thermal expansions or contractions) [4].

The cylinder head was modelled using Solidworks 2018 and was meshed and analyzed using Finite Element Analysis (FEA) Ansys 15.0. The analysis was done in two parts. A transient thermal analysis was done after which the results were then transferred to the transient structural analysis. The temperature induced stress from the former was the thermal load used in the stress analysis. Figure 3 shows the interface of the transient thermal and transient structural analyses

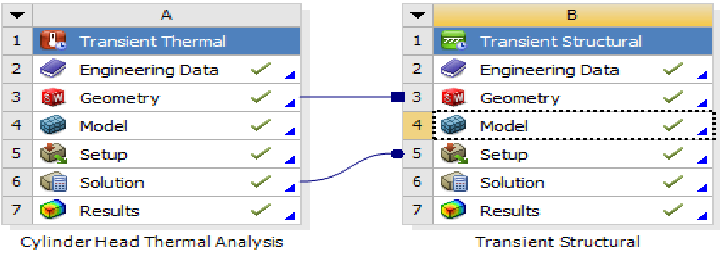


Figure 3: The interface of the transient thermal and transient structural analyses

2.1 Mesh

A mesh study is performed on a model to ensure sufficiently fine sizes are employed for accuracy of calculated results [5]. In this study, meshing was done with an adaptive mesh sizing and curvature conformation to ensure that the mesh can sufficiently account for small faces of the fins on the cylinder head. Figures 4 and 5 show the imported body and the mesh generated on the 3D model of the cylinder head.

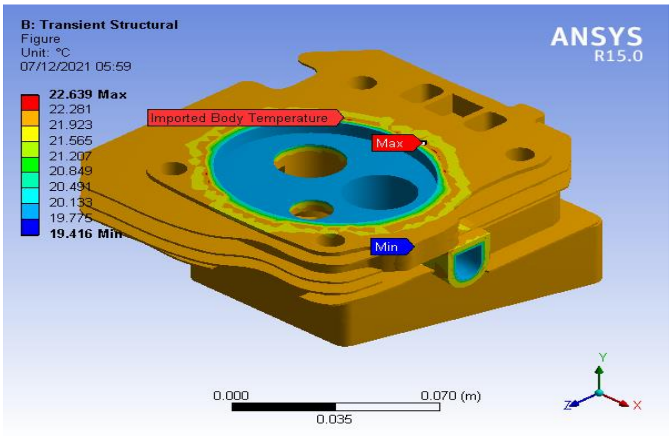


Figure 4: The imported 3D model of the Cylinder Head.

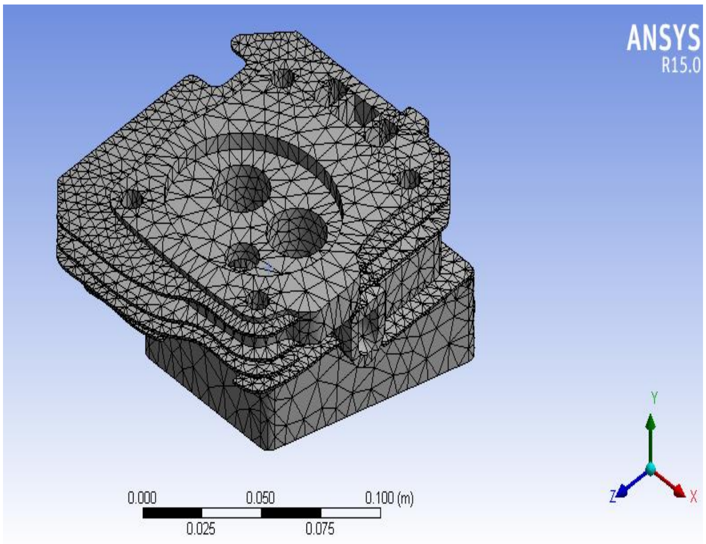


Figure 5: The mesh generated on the 3D model of the Cylinder Head

2.2 Load

Cylinder head is the most severing part to different loading conditions like pressure and high temperature, and the thermal load is one of the considered factors that is affected in cylinder head performance, and should be consider in design [6,7]. Temperature loads and natural convection were applied to signify the temperature rise and drops across the different strokes in an actual cylinder and the natural air flowing in the environment.

2.3 Temperature

The Table 1 shows the temperature loads on the cylinder head at different points.

Table 1: Temperature Loads

Steps	Time [s]	Temperature [°C]
1	0	22.0
2	0.2	75.0
3	0.4	150.0
4	0.6	200.0
5	0.8	150.0

Figure 6 shows the graph of the thermal load applied to the cylinder head faces against time

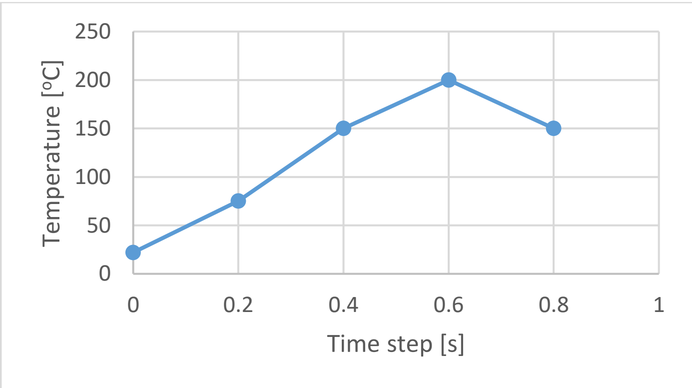


Figure 6: Thermal load applied to the cylinder head faces for particular duration

2.4. Convection

The Ansys inbuilt temperature dependent convection of air over a surface was applied to the cylinder head surface. Ansys then finds exposed faces and applies the loads. Table 2 shows the values of the Convection Coefficient of air at different temperatures.

Table 2: The values of the Convection Coefficient of air at different temperatures

Temperature [°C]	Convection Coefficient [W/m²·°C]
1	1.24
10	2.67
100	5.76
200	7.25
300	8.30
500	9.84
700	11.01
1000	12.40

Figure 7 shows the graph of the Convection Coefficient of air against different temperatures

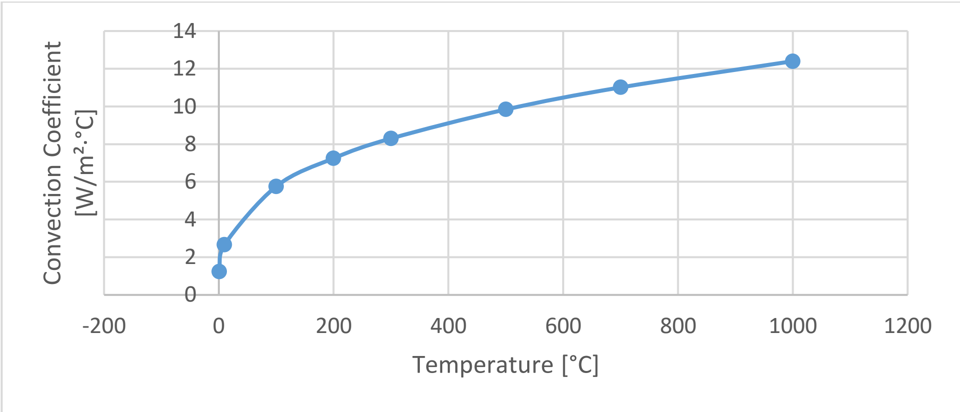


Figure 7: The graph of the Convection Coefficient of air against different temperatures

Figure 8 shows the temperature distribution throughout the cylinder head

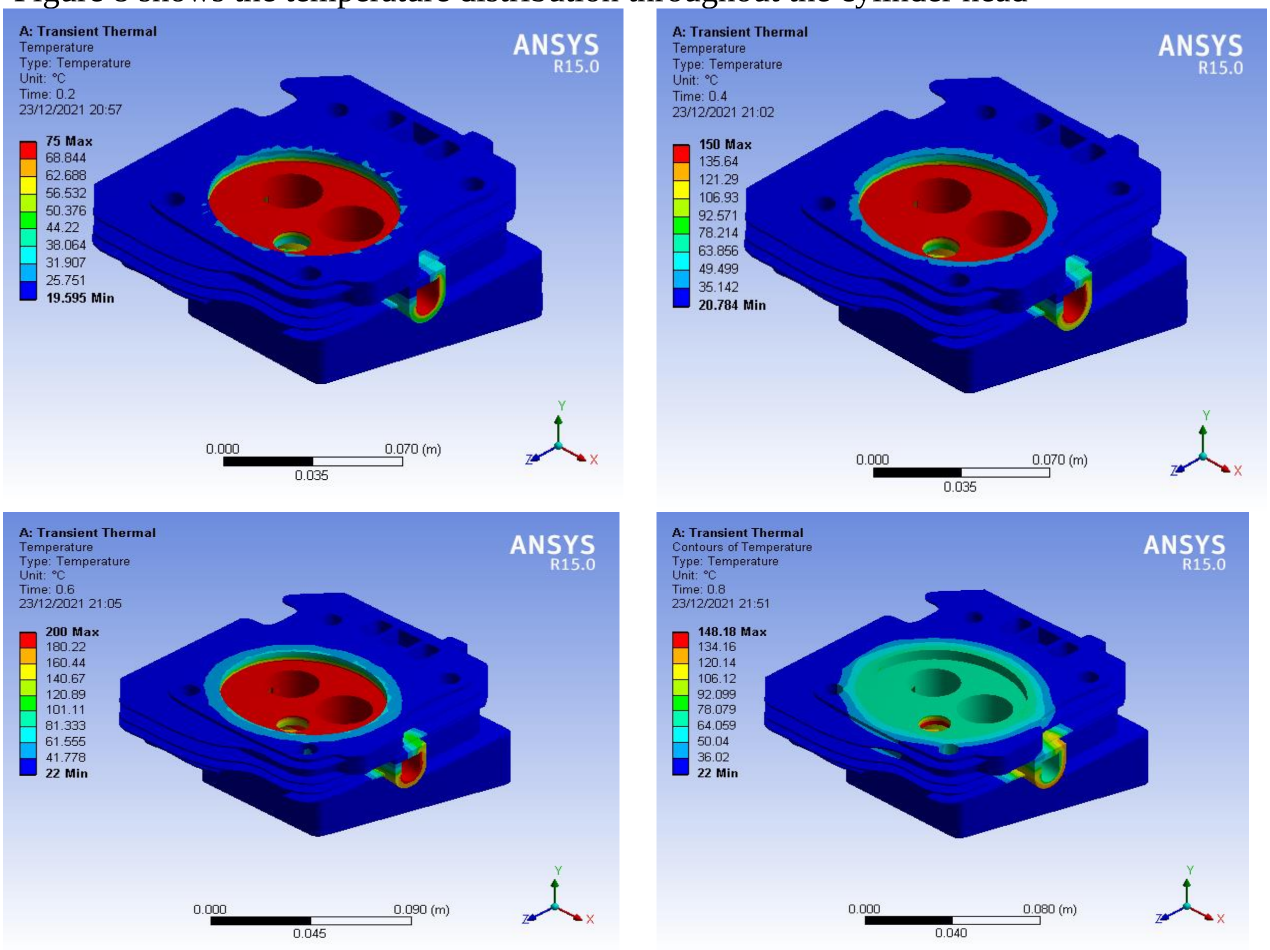


Figure 8: The temperature distribution throughout the Cylinder Head

From the transient thermal analysis of the temperature distribution throughout the cylinder head as shown in the contour plot of Figure 7, the red portion shows the part of maximum temperature of about 200^0C.

2.5. Total Heat Flux

Heat Flux is defined as the amount of heat transferred per unit area per unit time from or to a surface. The amount of heat transferred per unit time and the area from/to which this heat transfer takes place is shown in the analysis. Figure 8 shows the total heat flux of the Cylinder Head.

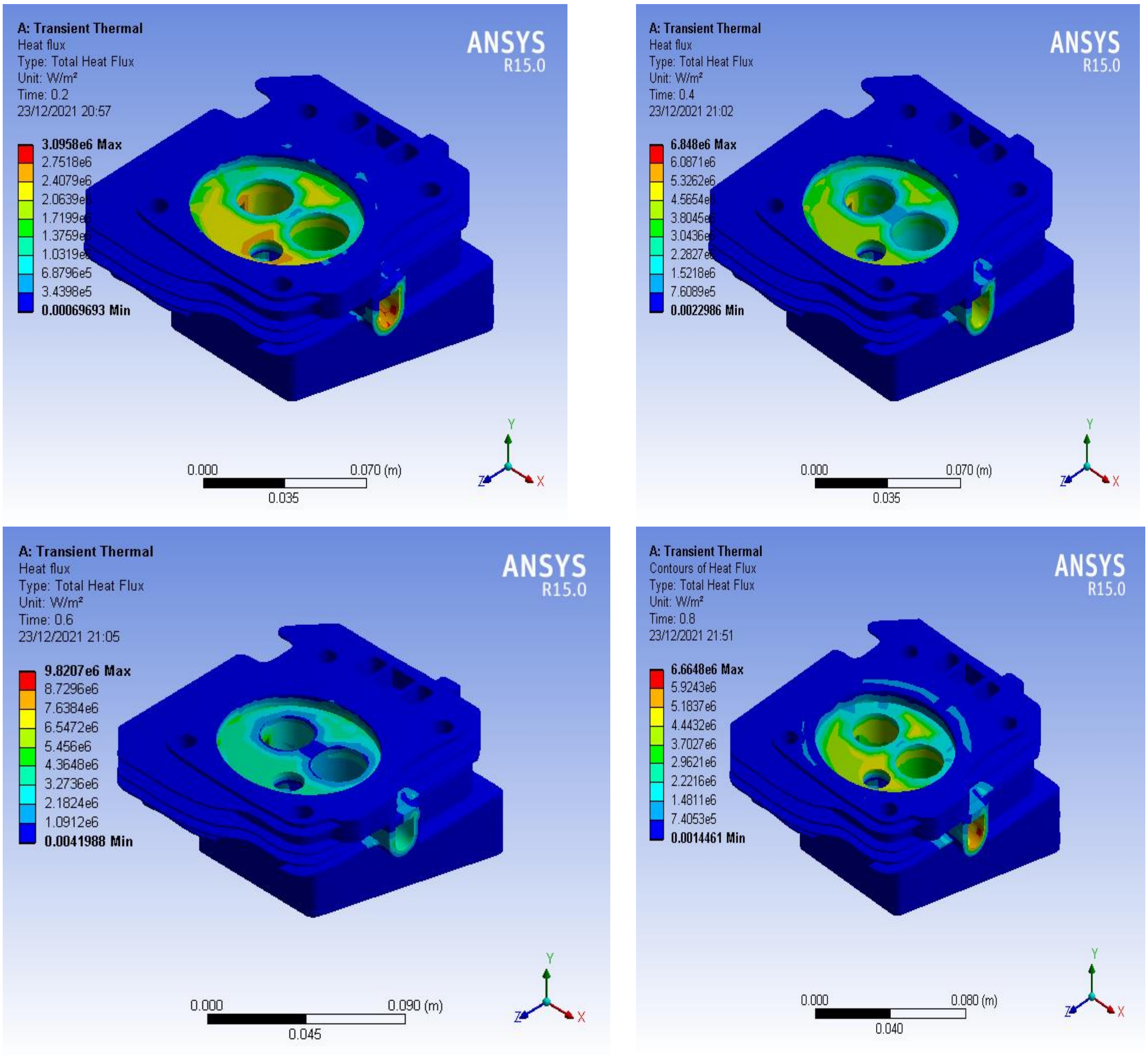


Figure 8: The total heat flux of the Cylinder Head.

From Figure 8, the red colour shows the maximum total flux of 9.8207 x 10^6 W/m^2 while the blue colour shows the minimum total flux of 0.00069693W/m^2. This means that the cylinder head is safe. Figure 10 shows the graph of heat flux against time.

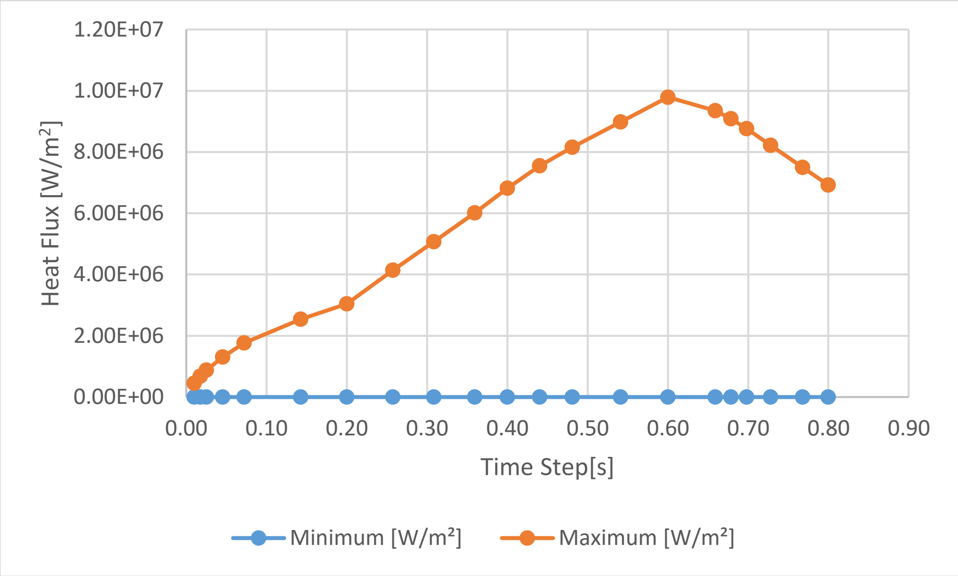


Figure 10: The graph of heat flux against time

2.6 Stress (Von Mises)

Figure 11 shows the graph of Equivalent stress against time

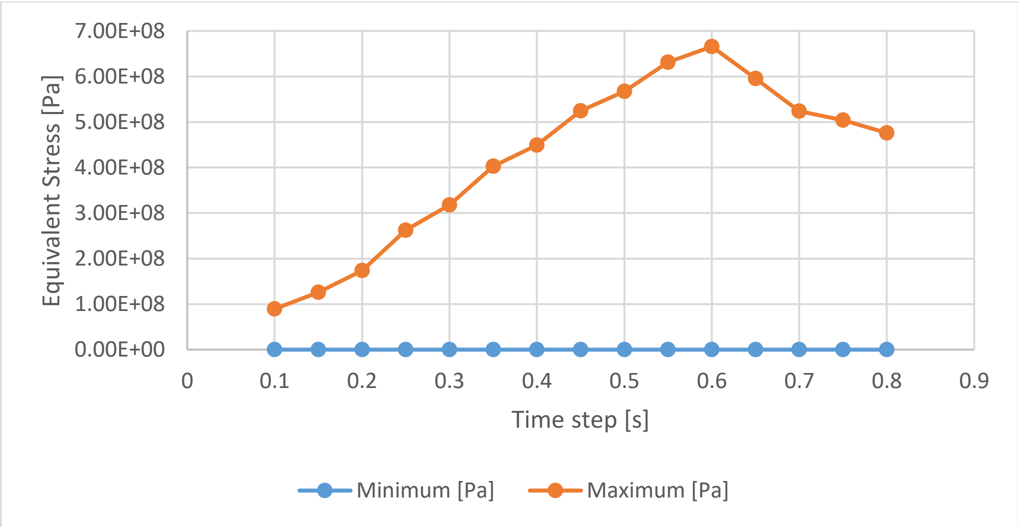


Figure 11: Graph of stress vs time

Figure 12 shows the contour plot for Von-Mises stress

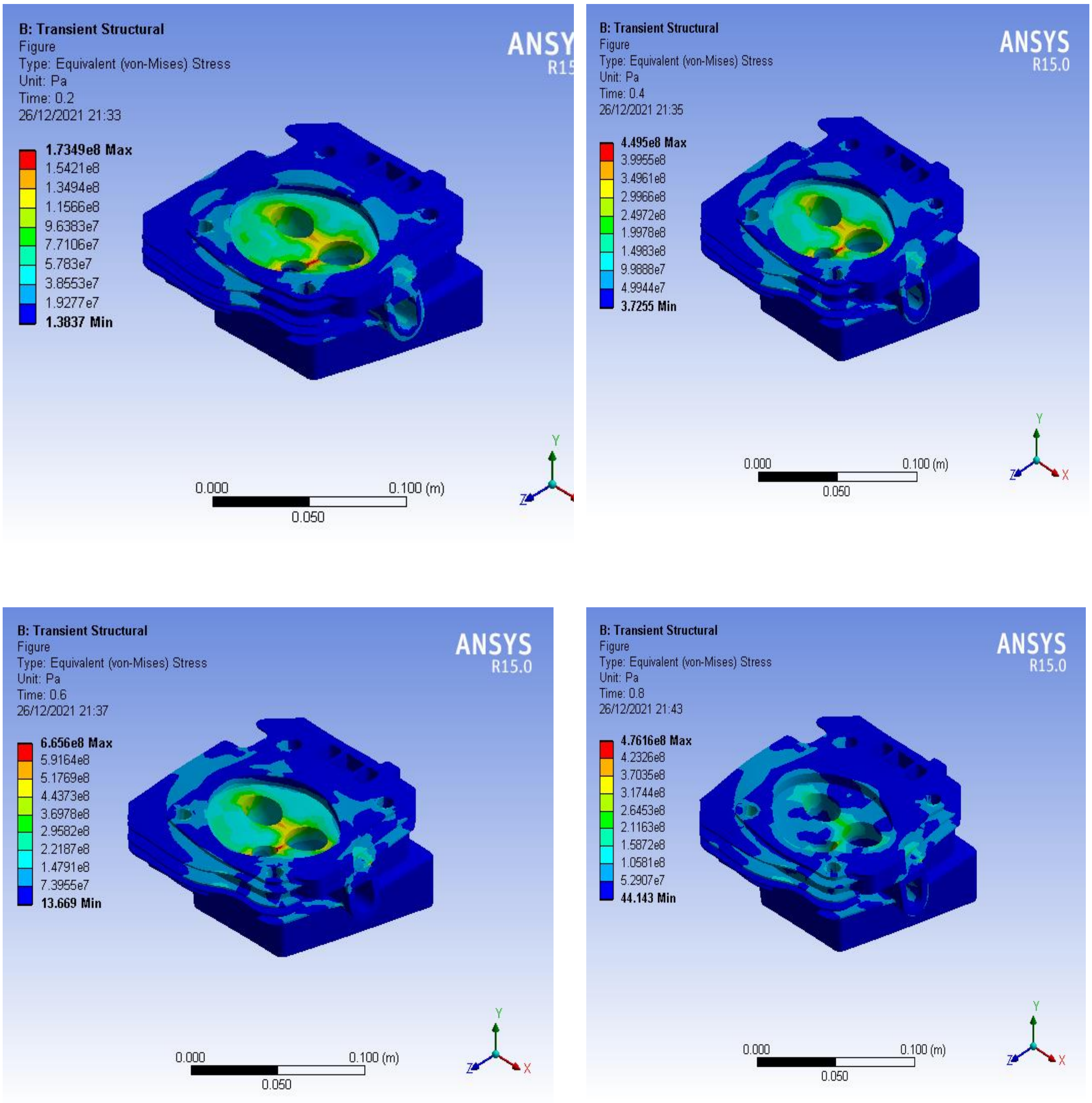


Figure 12: The contour plot for Von-Mises stress

From the Von-Mises stress contour plot, the maximum equivalent stress is 6.6560 x 10^8 Pa which the red part in the plot while the blue part shows the minimum value (1.3837 Pa) of the equivalent stress.

2.7 Elastic Strain

Figures 13 and 14 show the graph of elastic strain against time and the contour plots of equivalent elastic strain respectively.

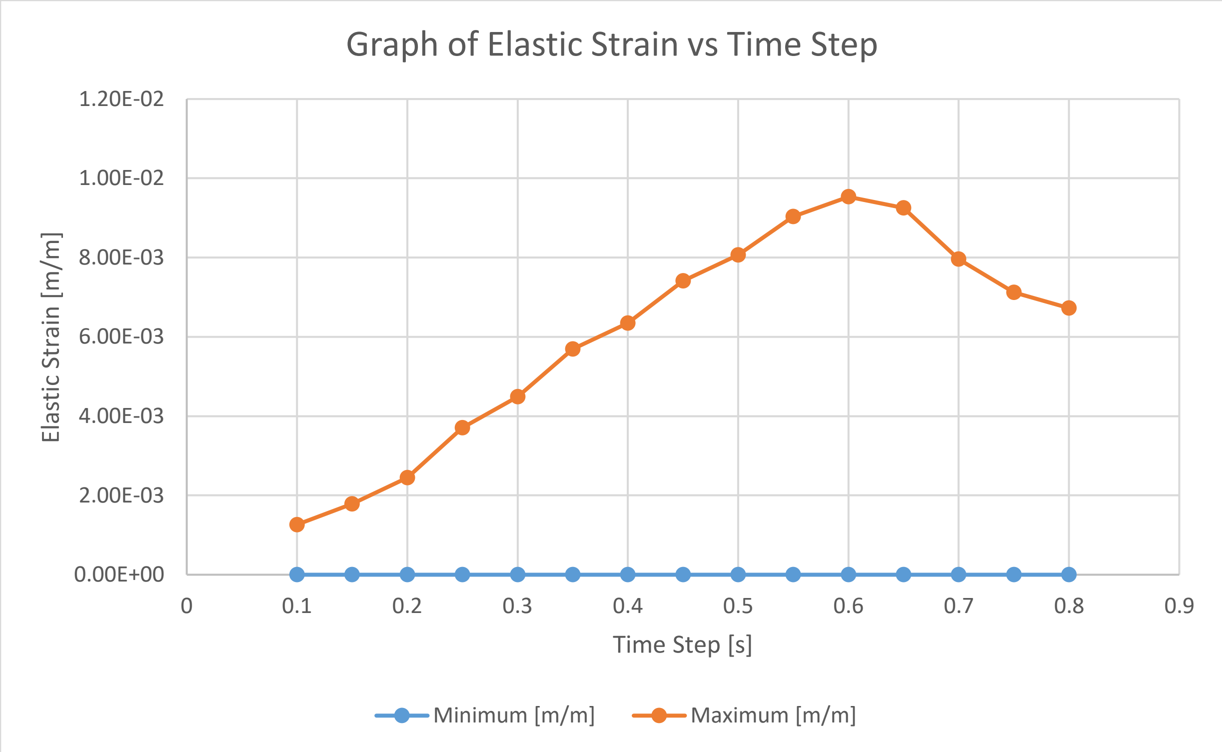


Figure 13: The graph of elastic strain against time

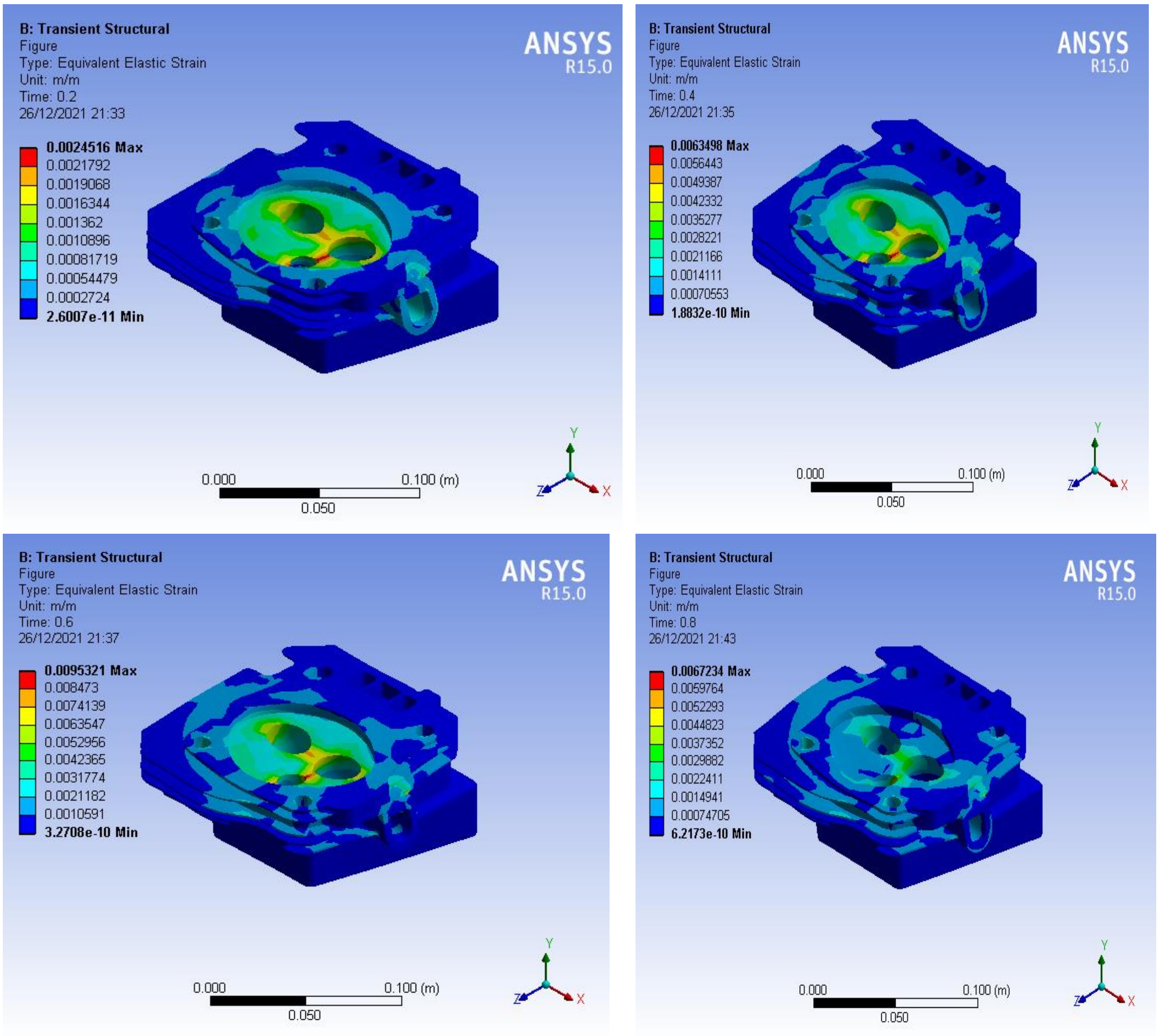


Figure 14: The contour plots of equivalent elastic strain

From the contour plot of the equivalent elastic strain, the maximum strain is 0.009521which is the red portion while the minimum equivalent elastic strain is 2.6007×10^{-11} which is the blue portion.

2.8 Deformation

Figure 15 shows the contour plot for deformation. From the plot, the part indicated with red colour has the maximum total deformation of 0.00025568m while the blue colour indicates the part with minimum deformation.

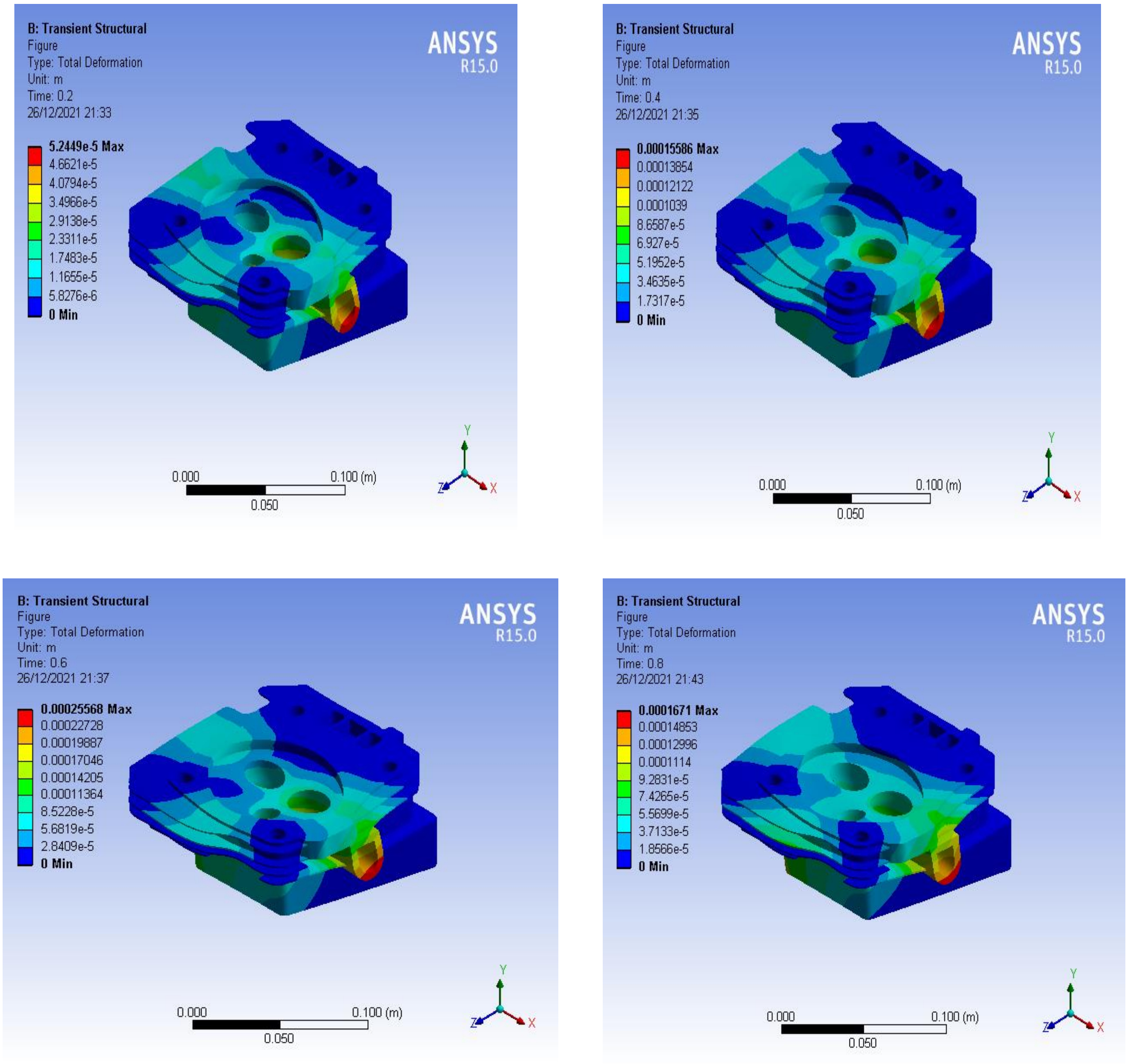


Figure 15: The contour plot for deformation

3. Fatigue analysis of the cylinder head

Fatigue is the initiation and the propagation of cracks in a material due to cyclic loading. To avoid sudden fatigue failure, fatigue analysis will be carried out on the cylinder head. Fatigue analysis includes some of the following. These are fatigue damage, fatigue life, equivalent alternating stress, fatigue factor of safety etc.

3.1 Fatigue Damage

Fatigue damage occurs when the stress at a point change over time. Any value of fatigue damage greater than 1 means there will be no damage to the design. Figure 16 show the fatigue damage of the designed cylinder head.

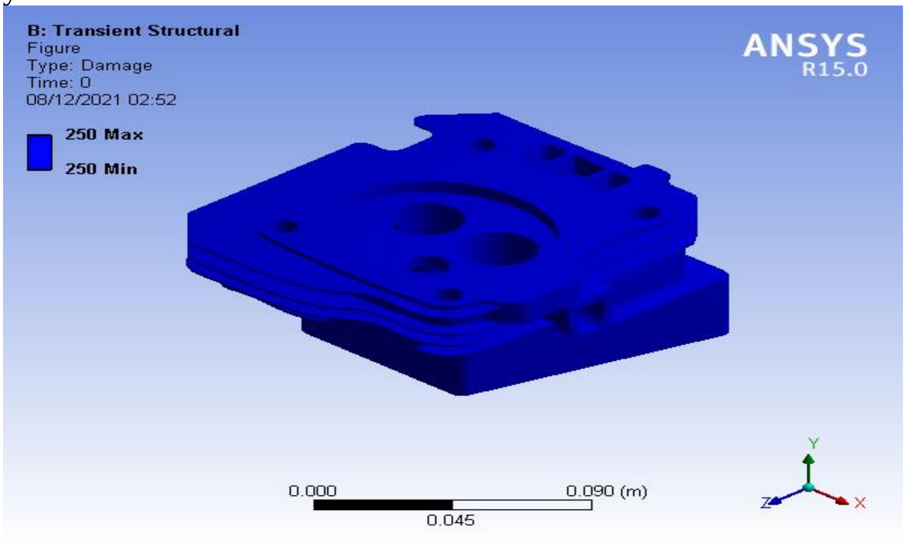


Figure 16: The Contour Plot of fatigue damage of the designed cylinder head

From the contour plot of figure 16, the fatigue damage value is 250. Since this value is greater than 1, it means there will be no damage to the designed cylinder head. The blue colour in all parts of the cylinder head indicates safety design.

3.2 Fatigue Life

Fatigue life is the number of loading cycles of a specified character that a specimen sustains before the occurrence of failure due to fatigue. Figure 17 shows the contour plot of the fatigue life of the designed cylinder head.

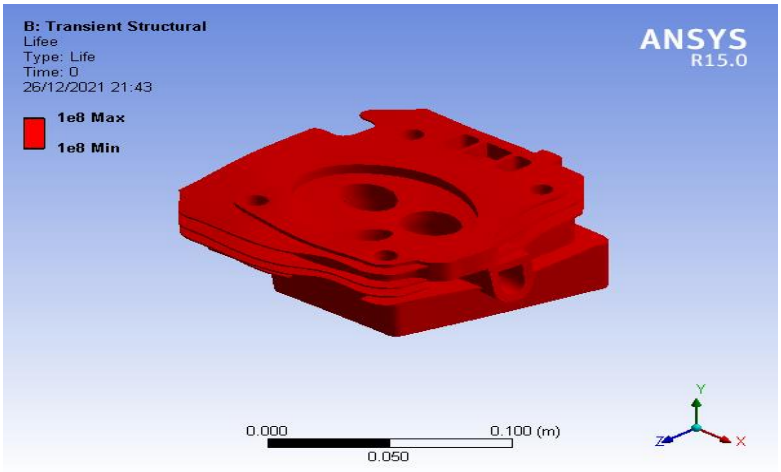


Figure 17: The contour plot of the fatigue life of the designed cylinder head

From the contour plot in Figure 17, the fatigue life of the designed cylinder head is 1 x 10^8 cycles.

3.3 Fatigue Safety Factor

This is the ratio of the yield alternating stress value to the working alternating stress value.
Figure 18 shows the contour plot safety factor for the designed cylinder head.

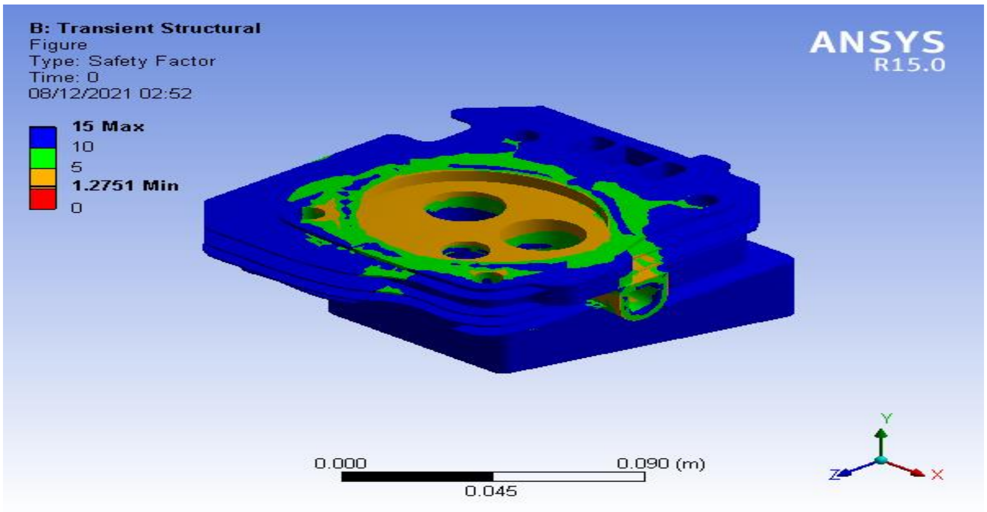


Figure 18: The contour plot safety factor for the designed cylinder head

From the contour plot in figure 18, the minimum safety factor is 1.2751 and the maximum is 15

3.4 Fatigue Sensitivity Analysis of the Cylinder Head

Fatigue sensitivity chart shows how the fatigue results change as a function of the loading at the critical location of the model. It shows how life of the model is affected by cyclic loading. Figure 19 shows the available life (cycles) of the material if the load is repeatedly applied. From the plot, it can be seen that the available life is up to 1 x 10^8 cycles which is constant up to 80% of the current load. Beyond 80% loading, the available life started decreasing until it reaches a critical fatigue life of 1.336 x 10^5 cycles at 150% loading.

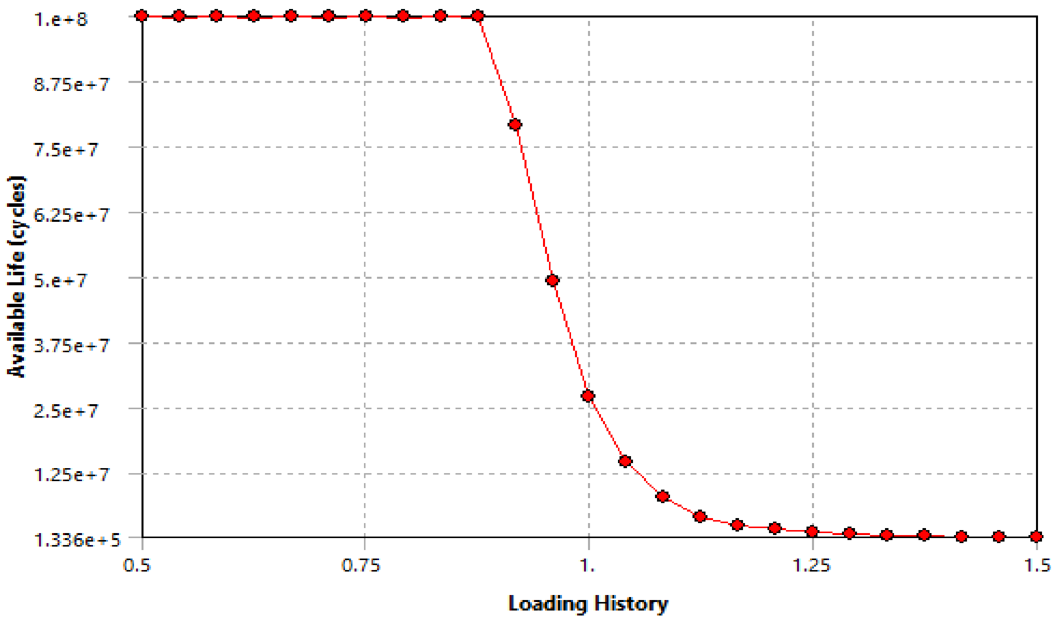


Figure 19: The available life (cycles) if the load is repeatedly applied

The summary of the results obtained in the difference analyses is shown in Table 3.

Table 3: Summary of the results obtained in the difference analyses

Type	Maximum	Minimum
Temperature distribution	200.000^0C	19.595^0C
Total heat flux	9.821×10^6 W/m^2	96.969×10^{-4} W/m^2
Equivalent (Von Mises) stress	6.650×10^8 Pa	1.384 Pa
Equivalent elastic strain	9.521×10^{-3}	2.601×10^{-11}
Total deformation	2.557×10^{-4} m	0.000m
Fatigue damage	250.000	250
Fatigue life	1.000×10^8	1.000×10^8
Fatigue safety	15.000	1.275

4. Conclusion

Thermal and structural analyses were successfully carried out on a locally developed cylinder head for 107cc 4-stroke engine block using Finite Element Analysis (FEA) ANSYS and the results obtained were satisfactory when compared with existing ones like the work of [8]. al as shown in Table 3.

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