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IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Improvement of a Lightweight Aluminium Cylinder Block Design Using Finite Element Stress Analysis

Mohamad A Arsah[1], Syed M A Syed Mohd Yusoff Sobbry[1], Tengku N A Tuan Kamaruddin[1*], Azmi Osman[2]

[1]Department of Mechanical Engineering, Kulliyyah of Engineering,
International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, MALAYSIA

[2]Perusahaan Otomobil Nasional Sdn Bhd, 40400 Shah Alam, Selangor, MALAYSIA

*Corresponding author

DOI: https://doi.org/10.30880/ijie.2020.12.05.005
Received 8 February 2020; Accepted 14 May 2020; Available online 30 June 2020

Abstract: A SAE technical paper (2012-01-0406) has discussed about the design and manufacturing method of a lightweight cylinder block made from cast iron. In applying the features discussed in the paper to an aluminium cylinder block with a different displacement, certain modifications need to be made to the previously proposed design. In addition to that and following the ongoing trend, many modern engines have a boosting system thus necessitating the engines to be designed to withstand a higher peak combustion pressure. The mentioned SAE paper has a proven design for a 2-liter cylinder block, but the maximum peak cylinder pressure is only about 85 bar representing the naturally-aspirated engine. Thus, the new proposed design simulating a boosted engine with maximum pressure up to 120 bar requires modifications to be made especially to the critical fasteners in terms of the bolt designs, engaged thread and the structural reinforcements of the bolt bosses. The cylinder block was modelled using CATIA V5 software and stress analysis of the baseline and proposed designs were done using the same software to analyse the critical area and force distribution. Two main areas have been investigated which are near cylinder head bolt thread area and near crankshaft bearing cap thread area. It was found that, the alterations manage to increase the factor of safety and eliminating the concentrated force at certain locations. The design modifications made can improve the factor of safety by decreasing the stress and adding more structural strength focusing on cylinder head bolt threaded area and crankshaft bearing cap thread area.

Keywords: cylinder block; engine design; finite element analysis; aluminium; lightweight

1. Introduction

An engine cylinder block is one of the important parts in an internal combustion engine because combustion process takes place in there. Thus, the structural design and material selection for the cylinder block must be precisely chosen and manufactured. Besides its function for the combustion process, engine cylinder block also is the heaviest component of the engine parts which constitutes up to 20 – 25 % of total engine weight [1]. The higher the engine block's weight means the higher the fuel consumption. Thus, it is important to design the cylinder block as light as possible as it will determine fuel consumption rate and emissions discharged to the environment.

Due to the above requirements, there is a growing trend in replacing the conventional steel and cast iron with other materials like aluminium and magnesium alloys [2, 3]. High strength, modulus of elasticity, wear resistance, ability to withstand vibrations and corrosion resistance are the must have material properties for the engine cylinder block manufacturing [4]. The material also should have low density to reduce the weight and high strength for the peak pressure.

*Corresponding author: tengku_dayana@iium.edu.my

To operate in high temperature condition when the combustion happens, it needs to have a low thermal expansion and high thermal conductivity to dissipate heat [5].

However, the design needs to be checked thoroughly so that it can withstand certain force and pressure applied to it. For the engine cylinder to function properly, it needs to have the requirements of wear resistance, long lasting, maintenance and able to withstand the combustion pressure [6]. Below are some cylinder block design features that need to be fulfilled to avoid failure [7]:

a. The structural strength and rigidity to withstand forces acting and minimize cylinder bore distortion.
b. The stiffness of top part to support the cylinder head and give sealing to the gasket.
c. The stiffness of bottom part and crankshaft bearing housing to minimize the distortion and wear of the bearing.
d. The stiffness of the rear part to support the transmission that will be attached to the engine block.
e. The size and weight need to be minimized.
f. Ease of manufacture and assembly.

In the SAE paper [8], the author has discussed the design and manufacturing method of lightweight cylinder block made from cast iron. Thus, this project aimed to apply the features to an aluminium cylinder block, with certain modifications to be made to match the material's properties. Following the current trend in downsizing engines which includes a boosting system to increase the power [9], thus in this project as well, the new engine cylinder should be able to withstand the higher peak combustion pressure as compared to the naturally-aspirated engine.

2. Research Methodology

The cylinder block design was built on the basis of the cylinder head which is attached at the top of the cylinder block must stay intact connected to the cylinder block when the engine is subjected to peak cylinder pressure as high as 120 bar for the boosted condition. Better design of the critical fastener areas which are near the cylinder head bolt thread area and near crankshaft bearing cap thread area are also necessary to accommodate higher cylinder pressure as compared to the naturally-aspirated engine.

2.1 Cylinder block model

In this project, the cylinder block was designed by using advanced modelling method in CATIA software. Basically, the key for this method is to use '*copy and paste special*' function in order ensure the design can be altered easily for each design variation. In this design, the model is divided into five parts which are *master*, *outer*, *inner*, *water jacket* and *final*. All these files are linked which each other. Thus, any alteration made to model either in *master*, *inner* or *outer* file will change the final design of the cylinder block in the *final* file. All the parts are design with their draft angles to comply with the casting process. The parameters and drawing of the engine cylinder block shown in Table 1 and Fig. 1 below.

Table 1 - Design parameters of single bay cylinder block

Description	Specification
Length of the engine block	97 mm
Height of the engine block	210 mm
Width of the engine block mating face	226 mm
Bore Diameter of cylinder	89 mm
Thickness of the cylinder wall	10 mm
Length of the cylinder	160 mm
Diameter of bolt	10 mm
The distance between the axis of two adjacent cylinders	97 mm

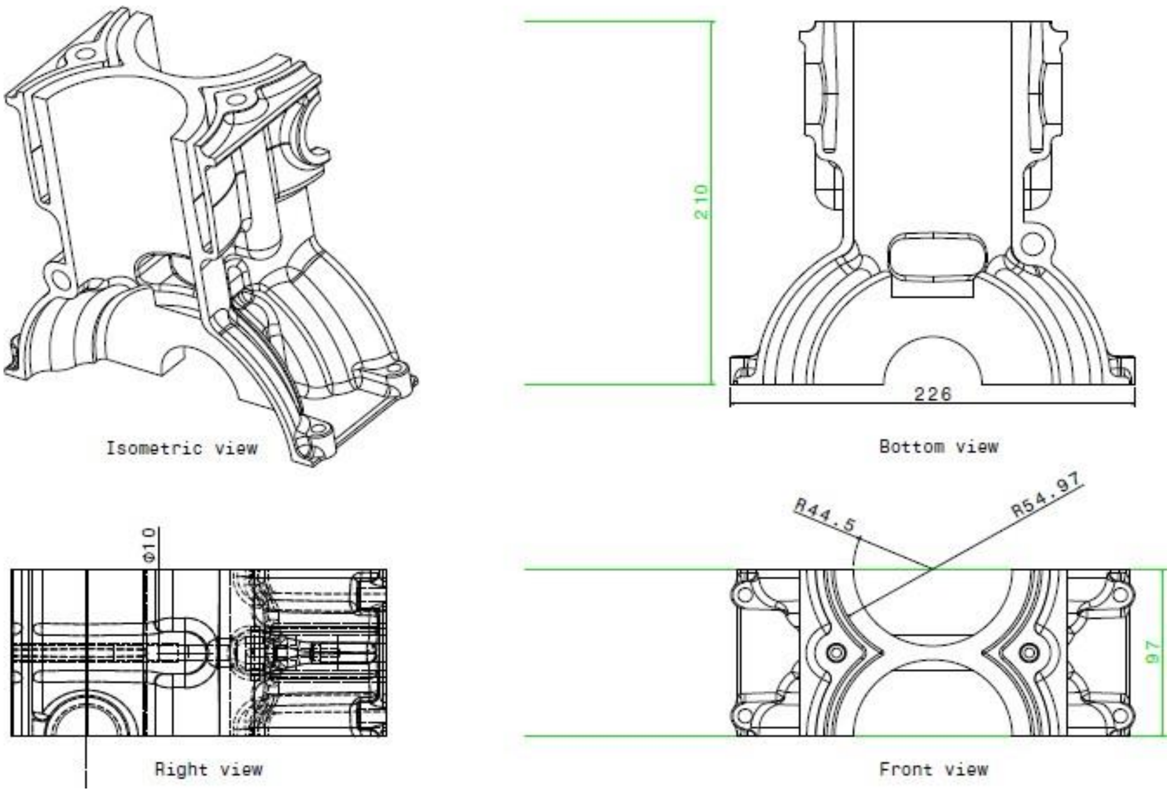

Fig. 1 - Drafting of single bay engine cylinder block

2.2 Model meshing & load calculation

The type of mesh selected for this model is *octree tetrahedron* with mesh size of 3.00 mm and absolute sag 2.26 mm. To analyse the strength of the cylinder block, the material attributes of the cylinder block was defined as shown in Table 2.

Table 2 - Material properties of the cylinder block

Description	Specification
Material	AC4B-T6 aluminium alloy
Young Modulus	74 GPa
Poisson's ratio	0.33
Density	2690 kg/m3
Yield strength	220 MPa

In this analysis, we assume only upward gas force acting on the cylinder head as shown in Fig. 2. Thus, to find the force applied, we need to use the mathematical equation of $F = PA$. The force obtained need to be divided by four as each cylinder will have four bolts to hold the cylinder block and cylinder head together [10].

$$Fg = \frac{Pmax\, \pi\, B^2}{4} \tag{1}$$

Where, F_g = Gas force acting on the cylinder head, kN
P_{max} = Maximum pressure, MPa
B = Bore diameter, mm

If 120 bar (12 MPa) pressure applied, the gas force would be:

$$Fg = \frac{12\,MPa\,\pi\,(89)^2}{4} = 75\,kN \quad (2)$$

The force applied on each bolt would be:

$$F_{bolt} = \frac{75\,kN}{4} = 18.75\,kN \quad (3)$$

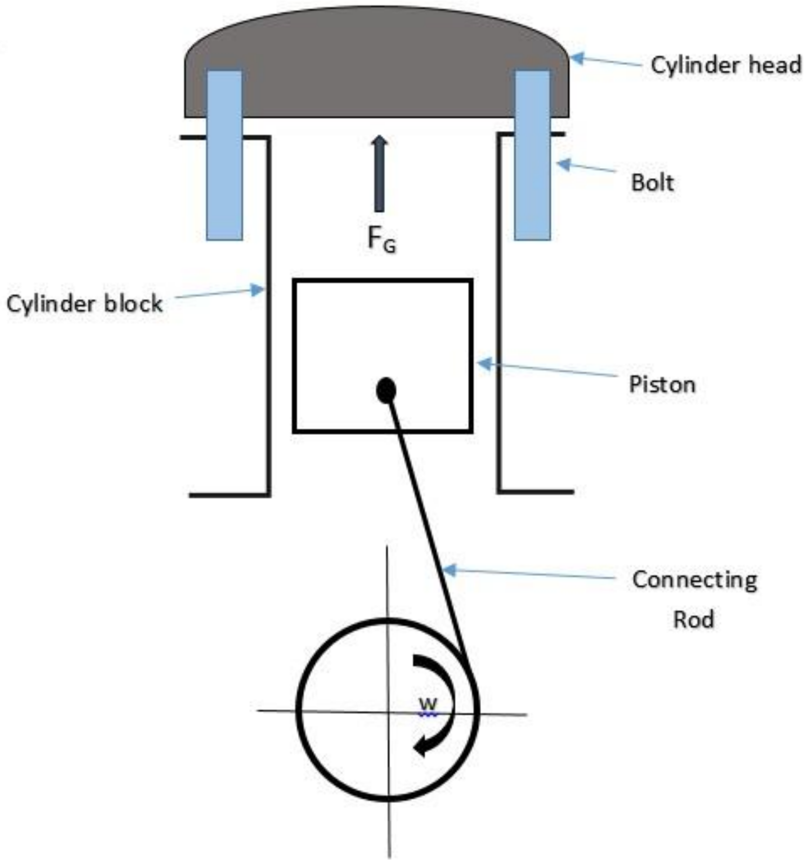

Fig. 2 - Gas force acting during combustion process

2.3 Boundary conditions

In this simulation the torque and bending moment acting on the bolt is ignored. Only upward force is considered for the cylinder head bolt thread area and downward force is applied for the crankshaft cap thread area. The cylinder block was clamped at six places like shown in Fig. 3 and Fig. 4 to ensure the block will not move.

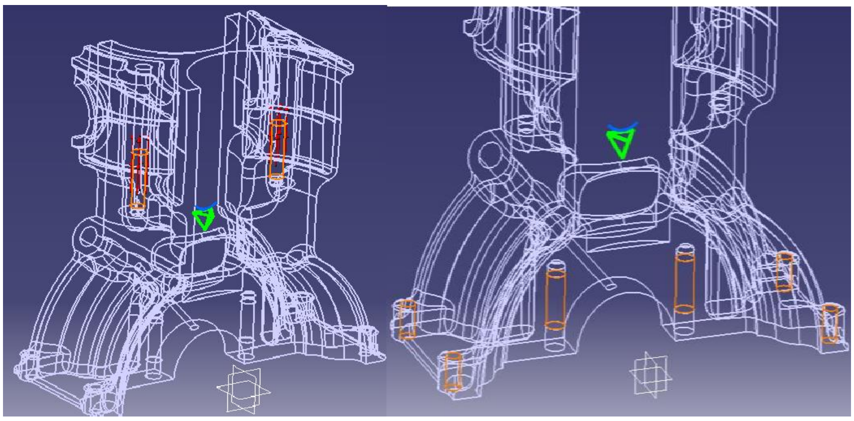

Fig. 3 - Wiring view of clamped area and force applied for cylinder head bolt thread area

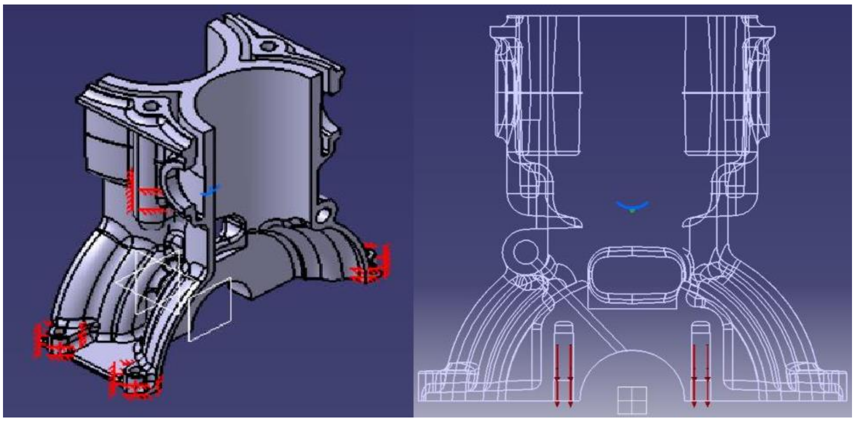

Fig. 4 - View of clamped area and force applied for crankshaft cap thread area

2.4 Variation of design improvements

Design improvements have been done at two main areas which are near cylinder head bolt thread area (Table 3) and near crankshaft bearing cap area (Table 4). These locations have been chosen because of they are exposed to high force during the combustion process up to 120 bar for the boosted engines. The cylinder head bolt thread area is the upper part of the engine block connected with the cylinder head while the crankshaft bearing cap area is the bottom part of the engine block connected with crankshaft.

Table 3 - Design variations near cylinder head bolt thread area

Option	Design variation
1	Baseline design
2	U-shape rib design
3	Flat rib design
4	Curve rib design
5	Curve rib with decreased window width

Table 4 - Design variations near crankshaft bearing cap thread area

Option	Design variation
1	Baseline
2	Rib at the starting of thread area
3	Rib at starting and end of thread area
4	Two extra bolts

3. Results & Discussion

Two main parts have been focused in this project which are near cylinder head bolt threaded area and near crankshaft bearing cap thread area. Von Mises stress (VMS) is the scalar stress value of von Mises yield criterion that is used to describe the yielding of materials begins when it reaches a critical value. A material is said to start yielding when its VMS reaches a critical value known as the yield strength under any loading condition.

$$Factor\ of\ safety = \frac{Yield\ strength}{Maximum\ von\ Mises\ stress} \tag{4}$$

3.1 Part A: Cylinder head bolt thread area

From the simulation for the baseline design, highest VMS obtained is 136 MPa which is 61.8 % of the yield strength, 220 MPa and safety factor is 1.61. Although the design is considered safe since the safety factor is more than one, it shows that the critical or red area is concentrated at the beginning of the bolt bores thread area near the cylinder head (refer to Fig. 5). Thus, it is necessary to make some modification at the bolt bosses' area to improve its safety factor and to distribute the concentrated force.

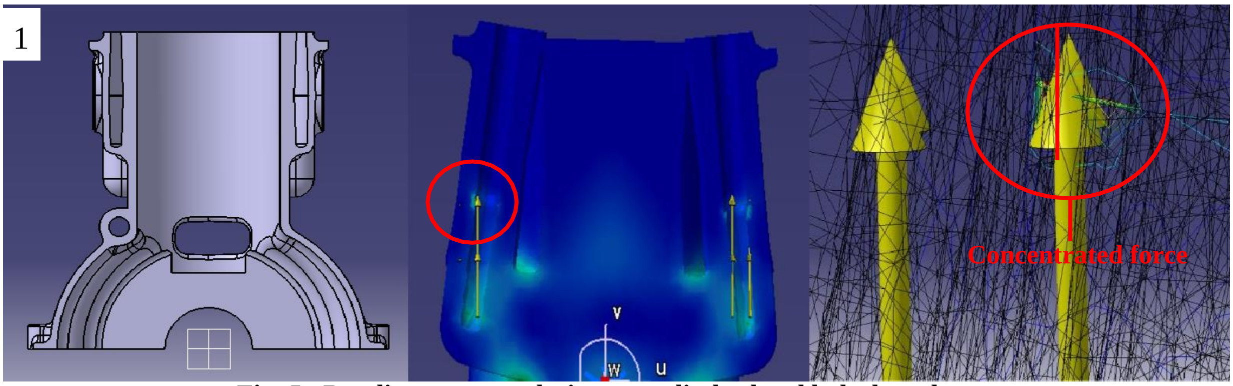

Fig. *5* - Baseline stress analysis near cylinder head bolt thread area

Table 5 is the list of design variations that have been done near cylinder head bolt thread area which were illustrated in Fig. 6. Five variations have been compared in term of their strength. In Option 5, the curve rib was added to the cylinder head bolt threaded area and the window width was decreased from 11m m to 6 mm. Also, window draft angle was increased from 2^o to 10^o.

Bar chart in Fig. 7 has shown that by adding a curve rib, it has the highest safety factor of 3.80. This shows that, curve rib is the best option because it is anchored to the water jacket and cylinder block thus make it stiffer and not easy to be detached from cylinder block. Meanwhile, u-shape rib is not suitable to be implemented because it is not anchored to any part of the cylinder block thus easy for the rib to be detached from the cylinder block.

Table 5 - Design variations near cylinder head bolt thread area

Option	Design variation	VMS (MPa)	Factor of safety
1	Baseline design	136	1.61
2	U-shape rib design	352	0.63
3	Flat rib design	67.1	3.27
4	Curve rib design	57.9	3.80
5	Curve rib with decreased window width	70.3	3.12

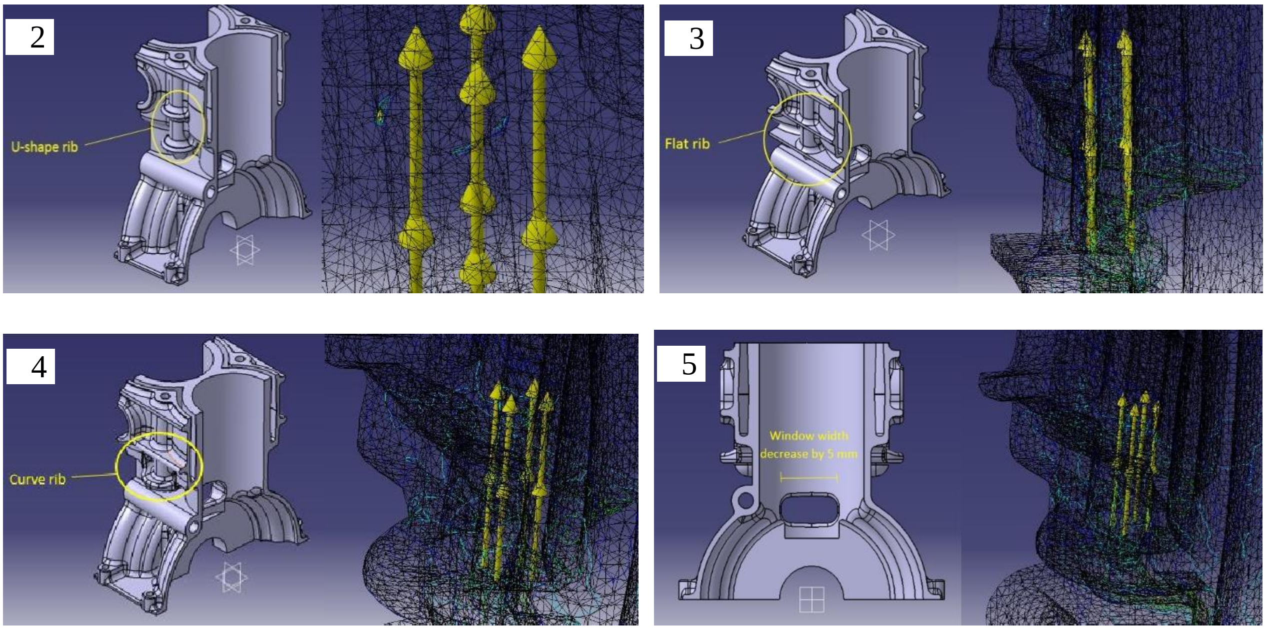

Fig. 6 - Variations of design near cylinder head bolt thread area

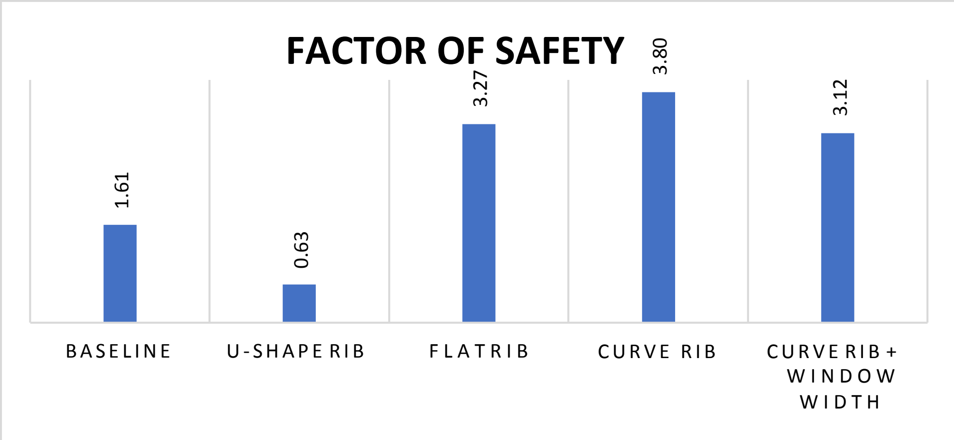

Fig. 7 - Factor of safety comparison for near cylinder head bolt area

3.2 Part B: Crankshaft bearing cap thread area

Table 6 is the list of design improvements that have been done near crankshaft bearing cap thread area. The baseline design (Fig. 8) has a safety factor of 1.15.

Table 6 - Design variations near crankshaft bearing cap thread area

Option	Design variation	VMS (MPa)	Factor of safety
1	Baseline	191	1.15
2	Rib at the starting of thread area	137	1.61
3	Rib at starting and end of thread area	127	1.73
4	Two extra bolts	77.2	2.85

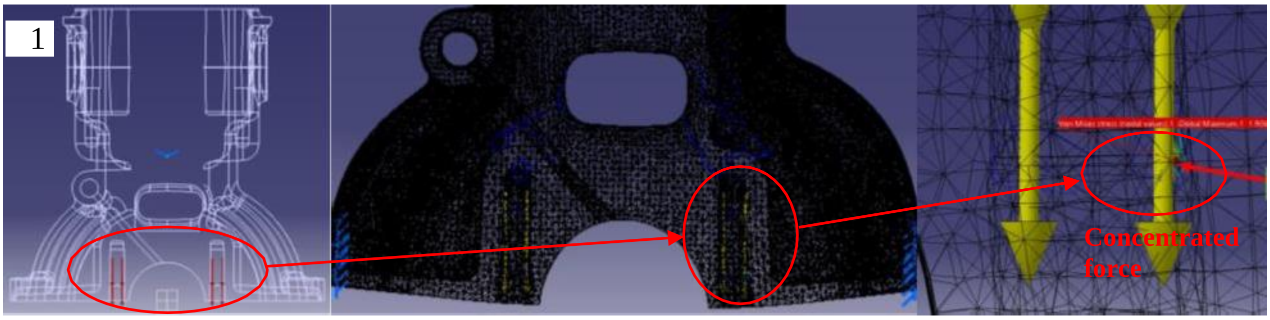

Fig. 8 - Baseline stress analysis near crankshaft bearing cap area

In Option 2 (refer to Fig. 9), a rib is added to the structure at the crank cap bolt so that the stress at the bolt is distributed. A rib at the beginning of the thread area is needed because the maximum stress occurred there as shown in the wire frame view. Factor of safety has increased to 1.61. Next design iteration in Option 3 has two ribs added at the starting and ending of the thread area. The maximum stress decreased, and factor of safety increased to 1.73.

The last design Option 4 added another two bolts to decrease the stress on the current bolts. The total force will be divided to six bolts for this design because the added bolt boss only will be added at the 1-2 and 3-4 bay of the engine cylinder block. The result has shown that this iteration has the lowest maximum stress than other. Factor of safety is the highest at 2.85 as shown in Fig. 10.

4. Conclusion

Through the variation of the design improvements, the results have shown that the modifications could be done to have a better engine cylinder block design. For the cylinder head bolt thread area, the curve rib addition has the highest safety factor and for the crankshaft bearing cap area, adding two extra bolts has shown greater safety factor than other modifications.

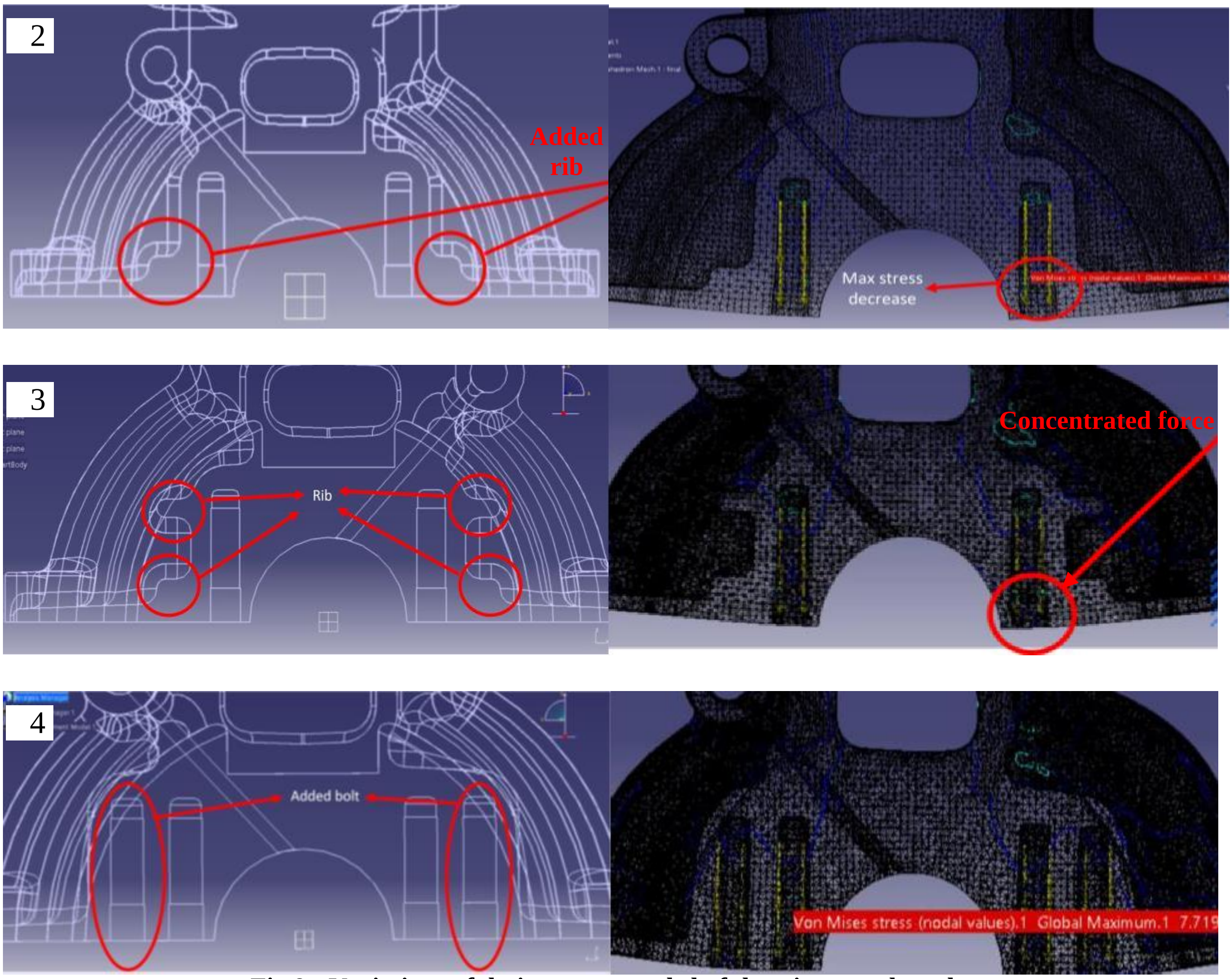

Fig 9 - Variations of design near crankshaft bearing cap thread area

Fig. 10 - Factor of safety comparison for near crankshaft bearing cap area

Acknowledgement

This work was supported by the Research Fund IRAGS18-054-0055 provided by International Islamic University Malaysia. We would also like to thank PROTON Sdn Bhd for supporting the project.

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