A NEW DESIGN OPTIMIZATION OF LIGHT WEIGHT FRONT LOWER CONTROL ARM

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ABSTRACT: This paper proposed the design optimization of aluminium cast for the front lower control arm was investigated. CATIA software was utilized to design the lower control arm. Hyperworks software was also used to analyse the structural strength and optimize the parts weight. The target of the new design was a 20% weight reduction from the existing part fabricated using steel material. The results showed a significant reduction of the overall weight as high as 25% with a fatigue life cycle approximately 396,000 cycles. Hence, the new design of front lower arm has fulfilled the criteria of fatigue life cycle and is suitable to be used in a C-segment passenger car.

KEYWORDS: *Casting; Topology Optimization; Aluminium Cast Alloy; Lower Control Arm; Automotive*

1.0 INTRODUCTION

Electric-mobility, CO2 emission limits, gasoline, global warming and energy prices are some of the factors driving lightweight automotive design[1]. Lightweight design requires suitable, economic manufacturing technologies in addition to the use of lightweight materials. Hence, it is a challenge to automotive manufacturer to produce the lightweight vehicle without compromising their performance. Weight reduction enables the manufacturer to develop the same vehicle performance with a smaller engine, and such a smaller engine enables the use of a smaller transmission and fuel tank. With these ripple effects, it is estimated that 10% of vehicle weight reduction results in 8–10% of fuel economy improvement. Lightweight approach could be achieved in various ways. Criteria of lightweight path could be changing to a new material which is superior in the sense of mechanical properties without compromising the state of the current components properties [2]. The use of lightweight materials can help to reduce vehicle weight and improve fuel consumption. The pressure for weight reduction has driven a gradual decrease in the amount of steel and cast iron used in vehicles and the corresponding increase in the amount of alternative materials especially aluminum.

Aluminum alloy is widely used in automotive industry in order to give lightweight vehicle and improve energy efficiency [3]. Nowadays aluminum alloy is widely used in body structure and closure such as door, hood, trunk lid and others. For example, Ford F150, 2015 model mostly used Aluminum sheets for the body structures closure panels whereas the Cadillac ATS and CT6 used “mixed materials” on body structure using aluminum casting, high strength steels and sheet metals [4].

Two types of aluminum alloy that are extensively used in automotive industries are non-heat-treatable or work-hardening AlMg(Mn) alloys (5000 series alloys) which show a good combination of strength and formability and the heat-treatable AlMgSi alloys (6000 & 7000 series alloys) that obtain their required strength through the heat treatment cycle [5]. In terms of chassis components, most likely chassis applications use non heat-treatable aluminum alloy 5000 series because its shows good formability and weldability. However, aluminum alloys that have been exposed to long term heat treatment can give outstanding corrosion resistence [6]. Moreover, cast aluminium alloys (i.e A319, Adc 12 and A356) are used widely to fabricate engine conmponents such as flywheel, cap cam shaft and engine mounting.

There are many components involved in the front suspension assembly such as knuckle, lower control arm, spring, etc. This study focused on front lower control arm (FLCA) as a target lightwieght component. FLCA is a connecting linkage between knuckles to sub frame underneath vehicle. In general, lower control arm design needs to be robust to enable multi-loading and lighter weight as it serves as the main hardpoint alignment [7]. As a part of chassis structure components, it plays a major role in anchoring suspension of hard points for lateral and longitudinal loading [8]. In platform development of a vehicle, depending on vehicle crash strategies, lower control arm as well is to absorb or delay crash energy, particularly in crucial crash case such as 45° offset frontal impact.

The commercial part of front lower control arm is fabricated from metal stamping process [9]. The total weight for assembly part of front lower control arm is about 4.8 kg per side or 9.6 kg for both sides. Hence, there is a need to reduce the weight of the part as to fulfill the car manufacturer's target to reduce the fuel consumption of their vehicle. In general, lower control arm design must be robust to enable multi-loading and lighter weight as it serves as the main hardpoint alignment [10-11]. Therefore, a new design of lower control arm which utilizes cast aluminium alloys is needed to reduce the weight of the parts at least about 20% the minimum weight reduction that is required from Proton. Thus far, there is a very limited design that utilizes the I-beam concept to reduce the weight particularly in the automotive parts. Therefore, the design and optimization process which utilized the I-beam characteristics were carried out in this study. There are several optimization methods involved, such as topology and shape optimization process. In this study, topology optimization was used to optimize predefined constraint such as loading at all bush mounting. Fatigue analysis was then carried out to analyse the durability and robustness of the new design of the front lower control arm. The outcome of this new design would contribute to the reduction of weight and fuel consumption, especially for C-segment passenger car.

2.0 METHODOLOGY

2.1 Design Concept of Aluminium Cast Lower Control Arm

The initial conceptual design of FLCA starts with a solid design to get the basic shape based on current stamping FLCA using CATIA V5 as shown in Figure 1. Figure 2 shows the concept design of the front lower control arm. The general L-shape of current metal stamping front lower control is maintaied to avoid any major changes to the surrounding parts, the hardpoints of lower control arm and also to endure the same kinematics performance of lower control arm.

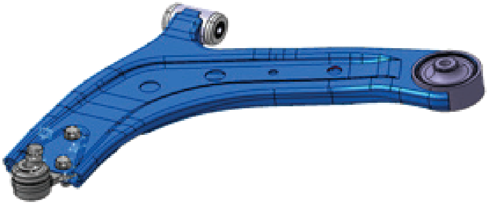


Figure 1: Current metal stamping of front lower control arm

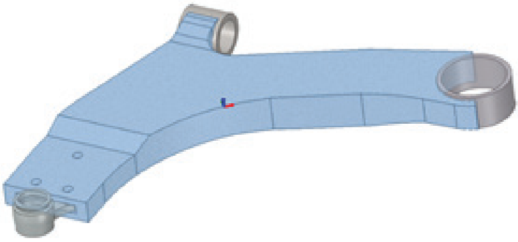


Figure 2: New concept design of front lower control arm

The initial concept design, then, underwent the optimization process and strength analysis in order to achieve the 20% of weight reduction for this part. The challenge in the design process after the optimization process was to consider the casting process and also the clearance issue with the surrounding parts in the suspension system.

2.2 Topology Optimization of Design Concept

In topology optimization process using Hyperworks Optistruct software, the base concept design was optimized based on standard suspension abusive loadcases loading at FLCA hardpoint as shown in Table 1. The topology optimization is a method to optimize the design in design space with the constraint of loads and some boundary conditions. It is a stress-based optimization through load path on the geometry [12]. It gives the best selection of design based on load path on material to reduce the weight of material. In terms of FLCA design, the non-load path areas based on suspension abusive loading were eliminated to reduce the material. This process was done in several iterations to get the optimum minimum of 20% weight reduction as shown in Figure 3.

Table 1: Suspension Abusive Loadcase

Analysis	Suspension Abusive Loadcases
Linear	Design Position
	Porthole Brake
	Ultimate Vertical
	Reverse Brake
Non-Linear	Oblique Kerb Strike
	Lateral Kerb Strike
	Porthole Corner

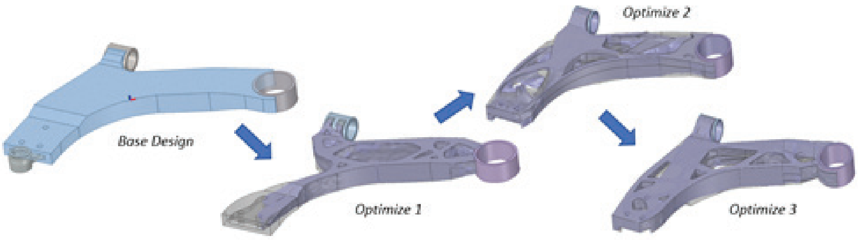


Figure 3: Topology optimization design process of FLCA

2.3 Structural Strength and Fatigue Analysis of Optimize Design Concept

Figure 4 shows the strength analysis of FLCA based on suspension abusive loadcase The structural strength analysis of optimized design FLCA was evaluated based on Proton suspension abusive loadcases which were derived from multibody dynamics (MBD) analysis of suspension system. The loadings from MBD suspension abusive loadcases were used to run strength analysis. The Finite Element (FE) model for FLCA design was setup in Altair Hypermesh software. The loading was applied at front bush, rear bush and outer bush mounting. Based on the suspension abusive loadcases, there are four loadcases under linear analysis; design position, porthole brake, ultimate vertical and reverse brake [13-15]. The strength results based on these four loadcases must not exceed the yield stress of material which was about 235 MPa for aluminum LM25. The other three loadcases were oblique kerb strike, lateral kerb strike and porthole corner under non-linear loadcases which yielded higher and severe loading compared with the linear loadcases. The non-linear loadcases strength results must not exceed the Ultimate Tensile Stress (UTS) of aluminum LM25 material which was about 250 MPa [16]. All the seven loadcases safety factor must achieve above 1.2 as per target requirement because the standard safety factor target for Proton vehicle parts must comply above 1.2 safety factor in order to pass the structural strength test for all parts in a vehicle [15].

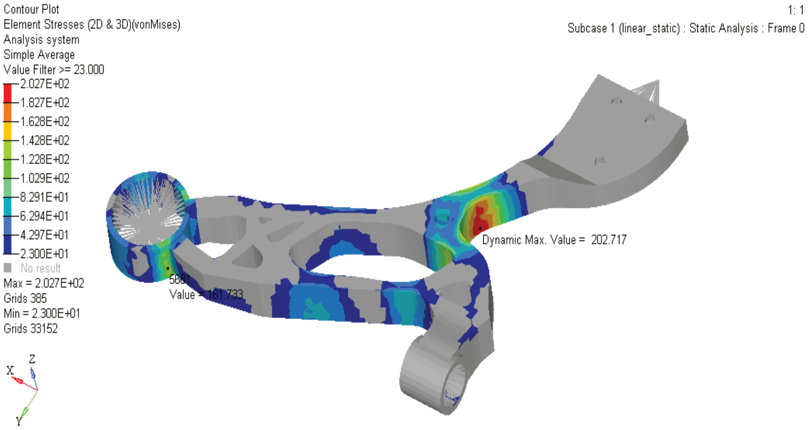
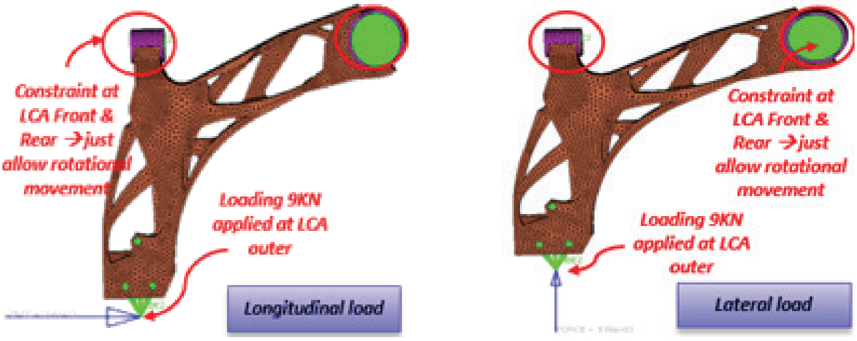


Figure 4: Example of structural strength analysis of FLCA based on Proton suspension abusive loadcase for static analysis loading equals to 800 N

Then, fatigue analysis was carried out using Hyperworks Software to analyse the durability and robustness of the new design of front lower control arm. The fatigue test was based on Proton fatigue test standard for front lower control arm. Two types of fatigue tests namely longitudinal load and lateral load fatigue test were used. The sinusoidal loading of 9000 N was applied laterally and longitudinally at lower control arm outer hardpoint as shown in Figure 5. The part must comply with the target of 300,000 cycles to pass the fatigue test.



(a) (b)

Figure 5: (a) Longitudinal loading and (b) lateral load fatigue test with 9000 N loading applied at LCA outer hardpoint model setup in Hyperworks software

3.0 RESULTS AND DISCUSSION

3.1 Optimization & Structural Strength Analysis of Aluminium Cast Lower Control Arm

The optimization design of aluminum cast FLCA consisted of several iterations to get the minimum weight reduction of 20% from the current design based on minimum weight reduction target for this FLCA part from Proton. The optimized design was based on Proton Suspension Abusive 7 loadcases. Loading was applied at FLCA hardpoints (FLCA front, FLCA rear & FLCA outer). After that, all the iteration design were evaluated. For design iteration 1 (see Figure 6), the optimization process was based on design/static position loadcase only. Based on the design iteration 1 optimization process, the non-loading path or non-critical loading area was discarded from the part to get the optimum weight. The design optimization process is very crucial in order to get the optimum weight and the part. The weight for design iteration 1 can reduce up to 37.53% which was about 2.124 kg. Then, the design was analyzed in terms of strength based on loading from suspension abusive loadcase. The structural strength results were evaluated based on maximum stress occurred at the part. The safety factor of the part were calculated based on the maximum stress occurred and the yield stress or ultimate tensile stress of material. The standard safety factor for Proton vehicle parts must comply above 1.2 safety factor [15]. Based on the strength results for design iteration 1, only two loadcases met the target safety factor above 1.2 which were design position in Figure 7(a) and ultimate vertical as shown in Figure 7(c). The other four loadcases as shown in Figures 7 (b), (d), (e), (f) and (g) did not meet the target safety factor of 1.2 especially on non-linear loadcases such as an oblique kerb strike, lateral kerb strike and porthole corner which yielded lower safety factor. Thus, the FLCA needed to be re-designed in order to meet the strength requirement.

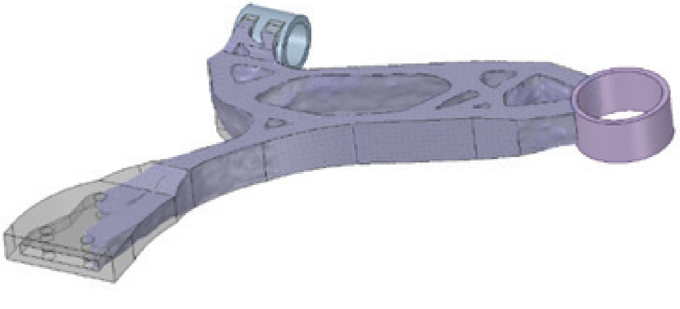


Figure 6: FLCA design iteration 1

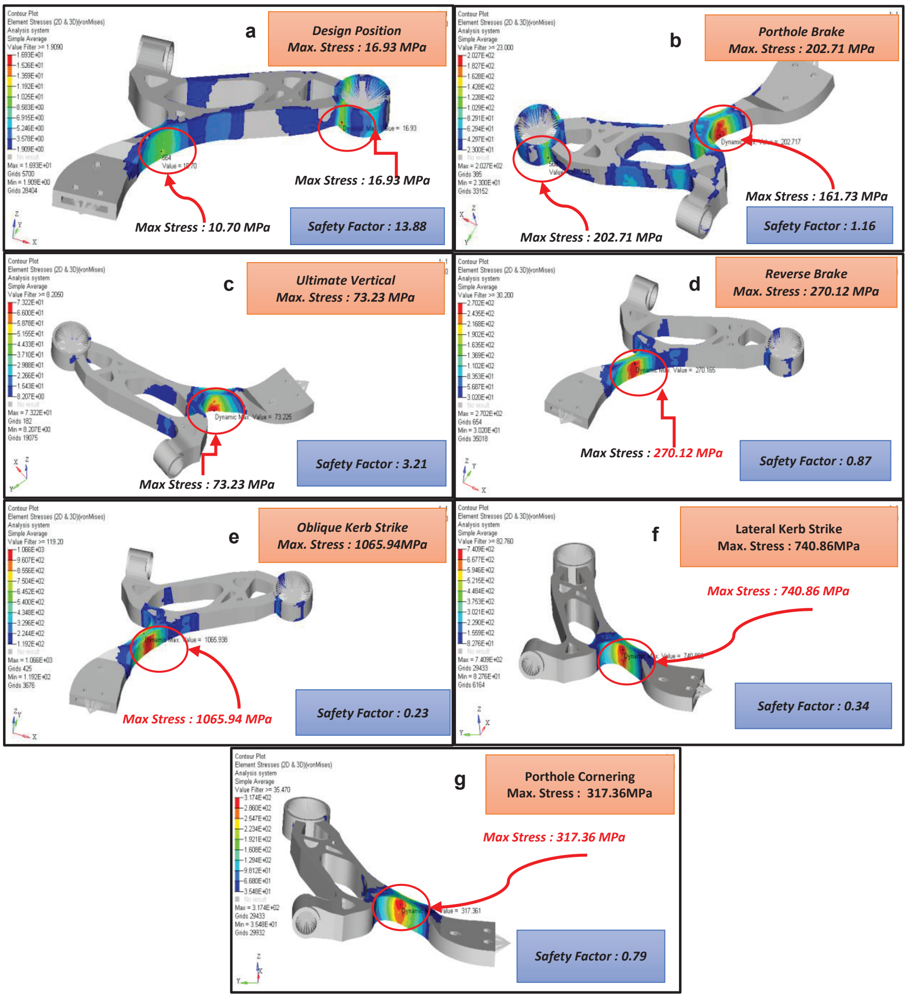
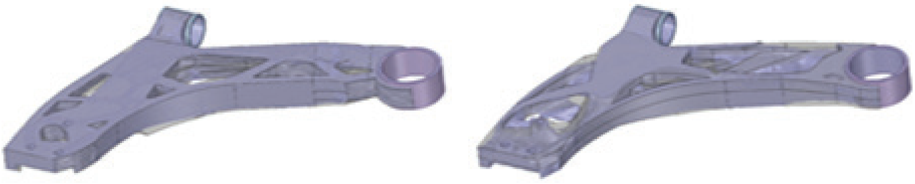


Figure 7: FLCA design iteration 1 strength analysis for linear laodcases (a), (b), (c) and (d) while for non-linear loadcases (e), (f) and (g)

Next, the design iteration 2 as shown in Figure 8(a) covered all 7 suspension abusive loadcases loading compared with design iteration 1 which only covered the design/static condition from suspension abusive loading. The discarded areas from loading path were reduced because all the loadcases were considered; about 23.41% of weight reduction which is about 2.604 kg compared with design iteration 1. For design iteration 3 as shown in Figure 8(b), the optimization process foused on a combination of non-linear loadcases for FLCA part which were oblique kerb strike, porthole brake, porthole corner and lateral kerb strike. Non-linear loadcases were prioritized because the loading from these non-linear loadcases were higher than linear laodcases. Hence, the loading is crucial because it can effect the structural performance of FLCA part. Based on this loadcase, the weight reduction was about 26.18%. The strength analysis for design iteration 3 was focusing more on non-linear loadcases. The maximum stress occurred for all three non-linear loadcases was still below the ultimate tensile strength (UTS) of material.



(a) (b)

Figure 8: (a) Design iteration 2 and (b) Design iteration 3

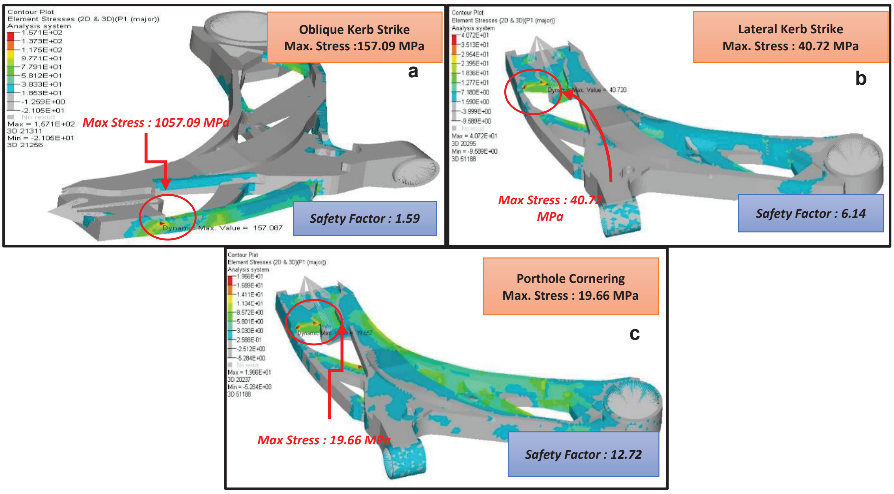


Figure 9: FLCA design iteration 3 strength non-linear analysis for (a) oblique kerb strike, (b) lateral kerb strike and (c) porthole corner loadcases

The safety factors of the oblique kerb strike, lateral kerb strike and porthole cornering were about 1.59, 6.14 and 12.72 respectively as shown in Figures 9(a) until 9(c) also by employing Equation (1). All these 3 loadcases met the target safety factor 1.2 upward.

$$\text{Safety Factor} = \frac{\text{UTS Material}}{\text{Maximum Stress}} \tag{1}$$

3.2 Final Design of Aluminium Cast Lower Control Arm

The final design of FLCA was based on the optimized design iteration 3 as shown in Figure 10. It needed to be re-designed using CATIA V5 software to get the smooth surface and shape for FLCA because the optimized design based on iteration 3 produced a roughly optimized shape for the FLCA. This final design also needed to include the manufacturing process that is tailored for the casting and machining process [17]. The weight for final design achieved 2.55 kg, which was about 25.0% weight reduction. Based on this final design, some constraints existed in ways to replicate the 100% design as per design iteration 3 due to manufacturing process and also a clearance issue with the surrounding suspension parts. The front bush housing must be replaced with an adaptable bush as shown in Figure 10 to overcome the clearance issue. Based on design iteration 3, the front bush housing is a part of aluminum cast with 7.5 mm thichkness which did not meet the target clearance above 5 mm with surrounding parts. The thickness reduction of cast front bush housing would give lower strength in that area to endure the load at front bush. The best countermeasure for this issue was to apply the adaptable bush using material SAPH 440 with 2 bolts connected between steel and aluminum cast.

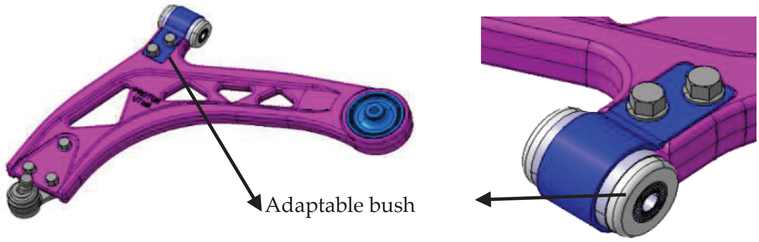


Figure 10: Final design of aluminum cats FLCA with adaptable bush

The strength analysis was conducted for final design of FLCA. Based on all 7 loadcases suspension abusive loading, the aluminum cast of FLCA and adaptable bush met the target strength requirement with safety factor above 1.2 for material aluminum cast LM25 and SAPH440 for adaptable bush. The safety factor of the part were calculated based on the maximum stress occurred and the yield stress or ultimate tensile stress of material. The standard safety factor target for Proton vehicle parts must comply above 1.2. The strength results of final design FLCA aluminum cast are shown in Figure 11.

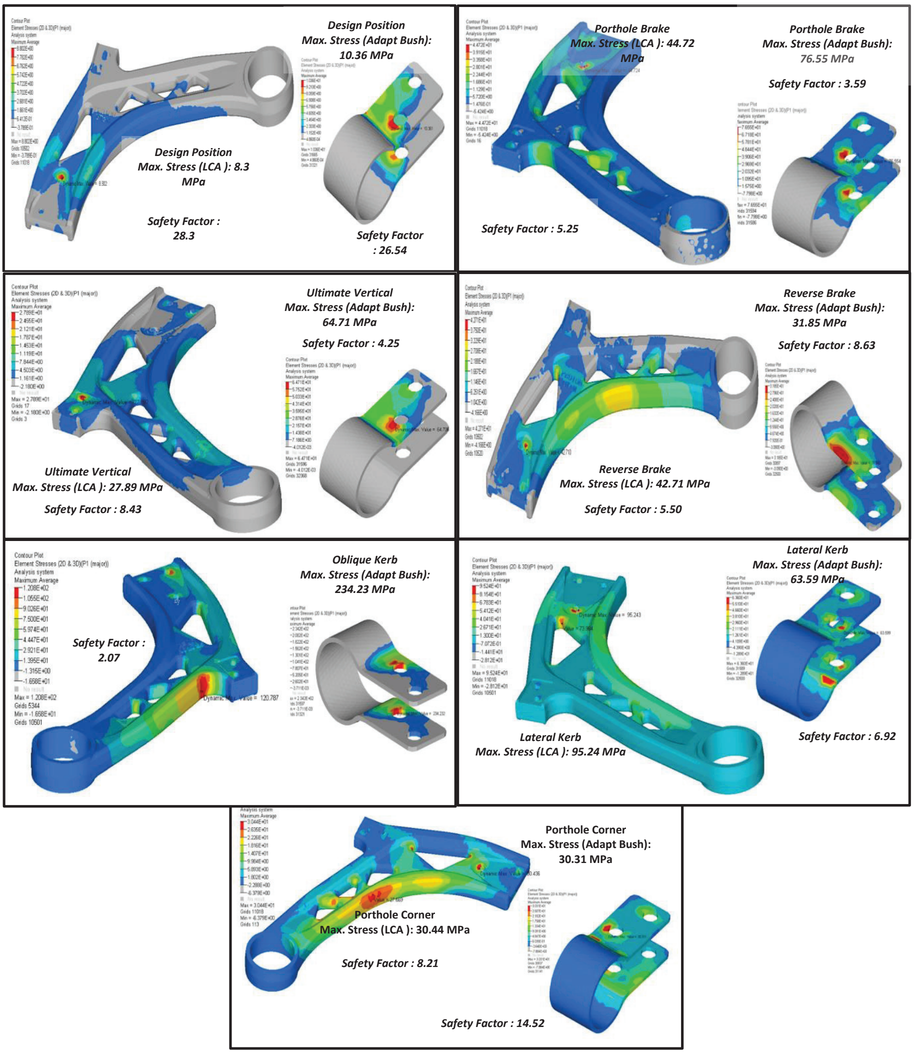
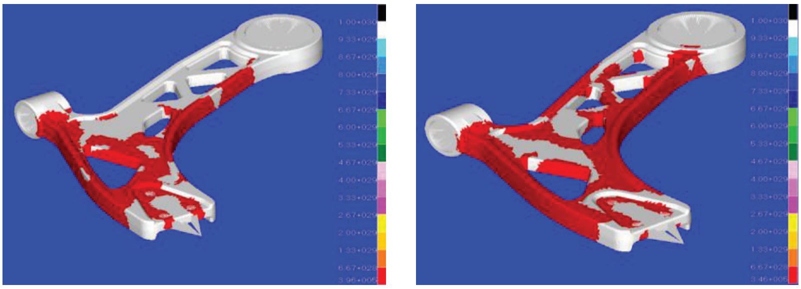


Figure 11: Structural strength analysis for final design

The fatigue test analysis was conducted in the final design of FLCA in order to ensure the strength fulfilled the requirement of 300,000 cycles before failure. Based on both lateral and longitudinal loadcases, the aluminum cast of FLCA met the fatigue test target of 300,000 cycles [15]. The longitudinal fatigue test achieved 396,000 cycles and lateral fatigue test achieved 346,000 cycles as shown in Figure 12. Therefore, it is proven that the performance of the optimized design cast aluminum alloy of FLCA fulfilled the required standard of the automotive part.



(a) (b)

Figure 12: (a) Longitudinal fatigue test (b) lateral fatigue test

4.0 CONCLUSION

The main objective of this research is to design a new lightweight of front lower control arm for the C-Segment vehicle using topology optimization process. This research can be beneficial to the automotive industry and university in terms of knowledge transfer, experience and expertise to explore in the areas of lightweight material and also manufacturing process which focus on new casting process. After several iterations of design and optimization process of aluminum cast FLCA, the weight reduction of aluminum cast FLCA achieved the target of 20%. Based on the final design concept of FLCA, the total weight is 2.55 kg, which is about 25% of weight reduction compared with the current metal stamping FLCA weight 3.40 kg and still maintains the structural strength performance and fatigue durability performance. The new design of this aluminum cast lower control arm has unique design compared with the current commercial design. It has shown some novelty in term of the design shape of the body part with a combination of the aluminium cast for body parts and also sleeve metal stamping for at rear lower control arm bush hardpoint. The I-beam cross section provides higher stiffness and moment for the parts to sustain the higher bending moment.

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