

DECISION ANALYSIS FOR OPTIMAL CONCEPTUAL DESIGN OF CONCURRENT BRAKE ACTUATOR

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ABSTRACT

Enhanced capabilities and customization in designs demand a thorough conceptual design phase for products or equipment. To ensure favorable outcomes, a comprehensive analysis of multiple design concepts is vital. This paper aims to conduct a decision analysis to determine the most suitable design for a concurrent brake actuator (CBA) among a range of alternative design concepts. It presents the development of the conceptual design of the CBA mechanism, which serves as a foundational mechanism design for future CBA development. Four mechanism design concepts were generated by utilizing the expanding curvature contour design, linear contour design, tilted position linear slope, and the nonlinear radius profile of the cam roller. The assessment of potential failures in the CBA concept design was performed by employing the risk priority number (RPN) within the framework of Design Failure Mode and Effects Analysis (DFMEA). The data obtained from DFMEA was utilized to conduct thorough analyses of motion and stress performance for each conceptual design using commercial software. Subsequently, the most optimal concept design for the CBA was chosen. This decision was reached by selecting the CBA concept design that achieved the highest score during the evaluation process, which employed a weighted decision matrix. According to the findings, the optimal CBA concept design was determined to be CBA Design B with the highest total score of 102 based on an RPN score is 32 and maximum stress of $3.647 \times 10^4 \text{ N/m}^2$. Its expanding linear contour design effectively distributes nonlinear brake force while minimizing failure risk, forming the foundational framework for future CBA development.

Keywords: *Optimization, concurrent brake actuator, weighted decision matrix, DFMEA*

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1.0 INTRODUCTION

Ongoing research aims to improve motorcycle safety, particularly by enhancing braking performance and vehicle stability [1]–[4]. Numerous strategies for brake force control, including combined brake systems (CBS) and antilock braking systems (ABS), were devised at this time. CBS improves the effectiveness of deceleration for motorcyclists. Its goals were to increase deceleration rates and reduce nosedive effects. The CBS reduces stopping distance by 40% by integrating the actions of the front and rear brakes through a single actuation control [5]. Furthermore, the CBS outperforms ABS in terms of deceleration distance on surfaces with high friction [6]. However, the CBS may still cause wheel lock under hard deceleration [7], [8]. In contrast, ABS prevents wheel lock and improves the motorcycle's stability and stopping performance. The ABS may not detect certain dynamic instabilities, such as rear-wheel lift-up, necessitating manual control of brake force distribution to avoid collisions [9]. Therefore,

integrating CBS and ABS has the potential to significantly improve motorcycle stopping distance and vehicle stability [10]. These technologies offer riders of all talent levels and experience levels safety benefits [11]. Currently, industries are developing additional improvements to integrate CBS and ABS on motorcycles [12]. The combination of these systems has enhanced braking efficacy. Nonetheless, implementing both systems on a lightweight motorcycle with an engine displacement of less than 125 cc is difficult. Therefore, integrating a wheel lock prevention strategy directly into CBS could be a viable alternative [12].

According to the impact assessment conducted by the European Parliament, CBS is a more affordable braking technology for lightweight motorcycles than ABS. In 2012, the European Parliament passed a law mandating the installation of CBS on lightweight motorcycles. This rule has been in effect for new type-approved vehicles since 2016 and for all new vehicles since 2017. Consequently, the European Union (EU) has made CBS mandatory for lightweight motorcycles [5], [13]. Since April 2018, India has also mandated the use of CBS for lightweight motorcycles, followed by Taiwan and Japan. Other nations, including Brazil, Australia, and New Zealand, are also considering similar regulations. The majority of motorcycles in this category are equipped with either mechanical drum brakes on both wheels or a combination of a hydraulic disc brake on the front tire and a mechanical drum brake on the rear wheel. Therefore, a mechanical actuator is a practical option for these motorcycles' CBS mechanisms. A brake lever actuates the CBS mechanism, which simultaneously engages the front and rear brakes via cable links. The force distribution of this CBS mechanism is largely unaffected by the deceleration increment.

Recent studies have shown that the variable combined brake systems (VCBS), which permit variation in the distribution of brake force, can attain high braking performance [14]. Maintaining an ideal nonlinear brake force distribution during deceleration is necessary to maximize braking effectiveness. This ideal distribution is achieved when both wheels lock up simultaneously during braking [15], [16]. To accomplish this, the present study proposes employing the Concurrent Brake Actuator (CBA), which was introduced in prior work [17]. The CBA serves as a regulatory mechanism for achieving the necessary non-linear distribution of brake force between a motorcycle's front and rear brakes. To achieve the desired non-linear force distribution, the moment-arm ratio must increase proportionally to the intensity of the actuation force. To effectively control this task, a passive compliant actuator is considered highly suitable due to its ability to modulate the moment of force during actuation [18], [19].

Accordingly, the objective of this research is to propose a design mechanism for the CBA that can effectively control the desired non-linear distribution of brake force. This paper presents a conceptual design of the CBA mechanism as a foundation for future CBA development. As a result, four conceptual designs of the CBA mechanism were generated. To assess the feasibility of the considered concept designs, Design Failure Mode and Effect Analysis (DFMEA) was employed, alongside motion and stress analysis using commercially available software. The evaluation of potential failures in the CBA concept design was carried out by utilizing the risk priority number (RPN) within the DFMEA framework. The data obtained from DFMEA was then employed in conducting motion and stress performance analyses for each conceptual design. Subsequently, the most optimal concept design for the CBA was selected by considering the CBA concept design that achieved the highest score during the evaluation process using a weighted decision matrix [20]–[23].

2.0 METHODOLOGY

2.1 Conceptual design of the CBA mechanism

Based on the fundamental concept of CBA [17] and deriving inspiration from the passive compliant actuator, Figure 1 depicts four conceptual designs for CBA mechanisms. These designs were then converted into three-dimensional computer-aided design (CAD) models with dimensions of 120 mm (H) x 170 mm (W). The purpose of these mechanisms was to adjust the arm distance during

actuation, whether by hand lever or foot accelerator, to generate distinct output forces for the front and rear brakes.

The primary body of the initial CBA concept, known as CBA Design A, featured an expanding curvature contour design. In this conceptual design, the front and rear brakes were activated via the ball-bearing roller's central axis. By moving the arm relative to the primary body, transmission of actuation forces was achieved. Specifically, the movement of the main body stretched the springs by causing the ball-bearing rollers to transverse the expanding curvature contour. This action facilitated the ratio-dependent control of a nonlinear moment arm function. Specifically, this was accomplished by increasing the horizontal distance between arm A and the primary body movement. The use of ball-bearing rollers assured a frictionless and smooth motion.

Alternately, CBA Design B investigated the feasibility of an expanding linear contour to accomplish the desired performance. Similar to Design A, the central axis of the ball-bearing roller facilitated the operation of the front and rear brakes. The main structure received actuation forces from either a hand lever or foot pedal. Arm A's horizontal distance increased as the primary body moved, while Arm B's distance remained unchanged. This relative movement between the arm and the primary body ensured that both brakes were activated. As a result, the front brake's actuation force was increased, while the rear brake's force was decreased. This configuration resulted in a nonlinear distribution of force across both brakes. The inclusion of a spring-maintained contact between the roller and the expanding contour, while the ball-bearing roller allowed for frictionless movement.

In the instance of CBA Design C, a predetermined arrangement was suggested for the primary structure. The primary structure was intentionally constructed with an inclined linear slope, and its motion was regulated by a pair of ball-bearing rollers. In line with earlier iterations, the implementation of ball-bearing rollers enabled seamless motion by minimizing friction. In the present design configuration, a single roller remained in a fixed position while the other roller traversed an elongated aperture. The displacement of the roller within the elongated aperture was directly correlated with the movement of the arm, resulting in the elongation of the spring and the traversal of the roller across the central structure. The arm was operated through the use of either a manual hand lever or a foot accelerator, facilitating the allocation of force to both the front and rear brakes. The activation of the front brake was achieved using the central shaft of the roller, which was situated within an elongated hole. In contrast, the rear brake was activated at a stationary position on the arm. It is important to acknowledge that the horizontal displacement of arm A exhibited an increase as the roller traversed the elongated aperture, while the horizontal displacement of arm B remained consistent throughout the process of actuation.

In contrast to the conventional fixed main body approach, CBA Design D presented a novel conceptual design that integrated a nonlinear radius profile for the cam roller. The synchronization of the cam roller's rotation with the movement of the primary body was achieved through the control of a hand lever or foot pedal. The transmission of actuator forces for the front and rear brakes occurred via the central shafts of the ball bearing roller and cam roller. The horizontal distance between the cam roller and the ball bearing roller was controlled by the rotation of the cam roller, while the contact force applied to the main body was regulated by a spring that was connected to both rollers. As the cam roller underwent rotational motion concerning the main body, the separation between arm A and arm B in the horizontal direction exhibited an increase, while the separation between arm A and arm B in the horizontal direction remained constant. The implementation of this mechanism led to a non-linear allocation of force between the front and rear brakes. The integration of a ball-bearing roller facilitated seamless motion devoid of friction.

2.2 Conceptual Design Evaluation

In this study, Design Failure Mode and Effect Analysis (DFMEA) as well as motion and stress analysis by commercial software were combined to conduct the evaluation. The utilization of the DFMEA methodology facilitated the identification of potential adverse consequences resulting from failures, as well as the underlying causes of these failures, and the development of strategies

to prevent them. This approach involved a comprehensive analysis of individual components and their interrelationships. The potential failure items associated with each concept design in the CBA were subsequently identified and subjected to analysis utilizing the risk priority number (RPN) formula.

A motion and stress analysis were performed by using the commercial software of finite element analysis (FEA). It was used to perform a stress performance analysis on each CBA conceptual design using the DFMEA data as well as to simulate the motion of the CBA. This analysis utilized assembly members, part contact, and a robust physics-based solver to determine the assembly's physical movements under the specified load. Figure 2 depicts the flowchart layout utilized for this analysis. A structural analysis was conducted on the components, considering the calculated assembly motion and forces. The analysis focused on evaluating the stress conditions experienced by the critical sections. Figure 3 depicts the geometry and boundary conditions (BC) designated to each component of the CBA concept design. In this analysis, a reference point was established on the fixed guide component. The constraints and applied load were selected following the CBA's guiding principles. To prevent components from penetrating during motion, Solid Body Contact was defined as the type of contact between components. This configuration was applied to each CBA concept design for the objectives of the analysis.

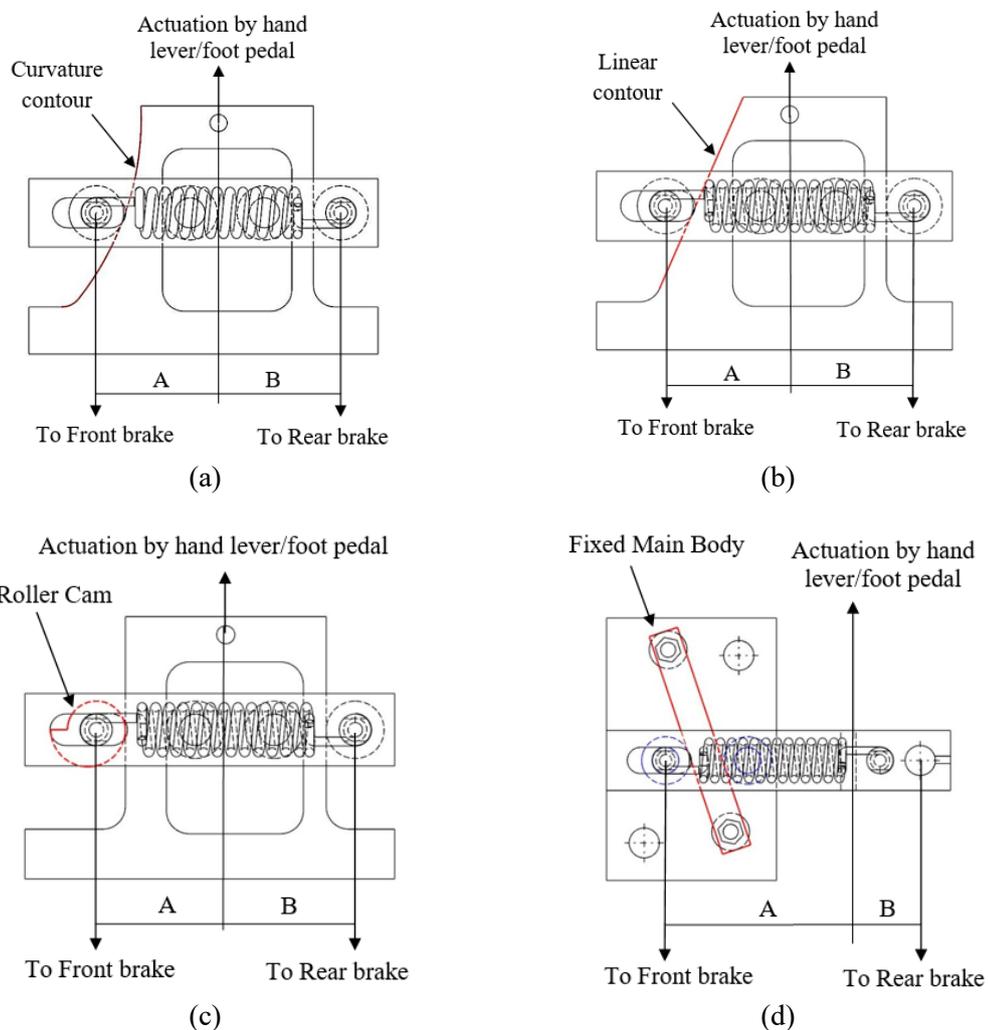


Figure 1. Schematic of CBA concept design; a) CBA Design A; b) CBA Design B; c) CBA Design C; d) CBA Design D

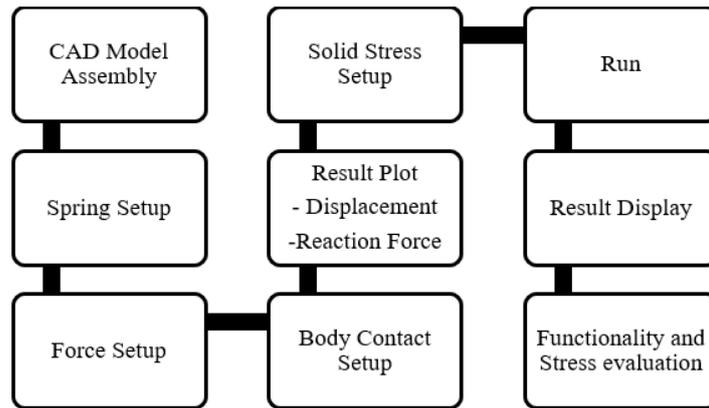


Figure 2. Motion Analysis Setup [17]

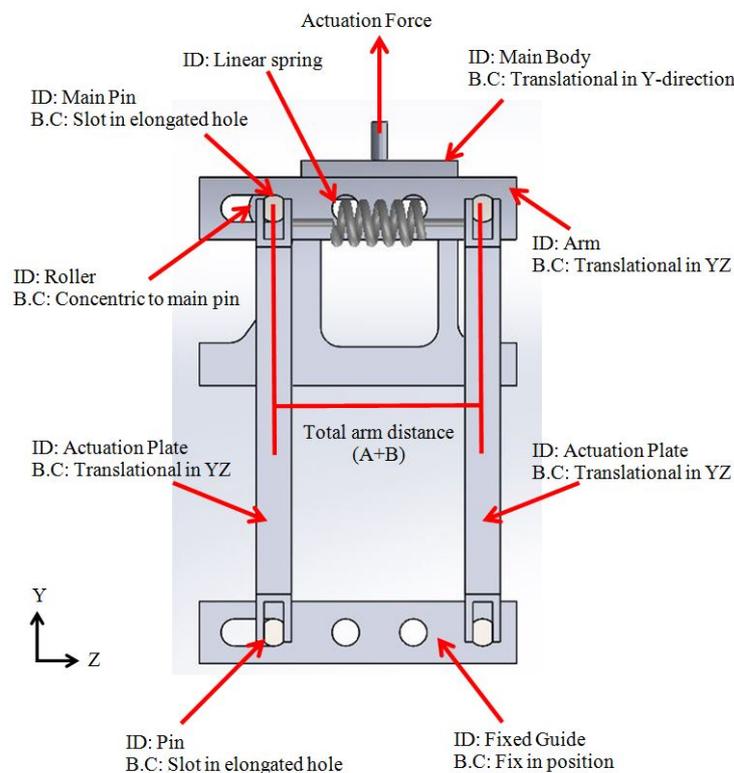


Figure 3. Boundary Condition Setup [17]

3.0 RESULTS AND DISCUSSION

3.1 Design Failure Mode and Effect Analysis

Based on a review of component connections and interactions, Table 1 details the probable failure points for each CBA concept design. The first column of the table defined each CBA design concept, while the second column detailed the probable failure items and their related functions within each CBA. It was determined based on this column that the primary pin and cam roller were potential failure areas.

CBA Designs A, B, and D made extensive use of the primary pin mechanism to assist the application of force for triggering the front and rear brakes, letting them to adjust to the increasing

contour of the main body. The dynamic contour exhibited a notable influence in governing the non-linear allocation of force to the braking system. On the other hand, the horizontal distance of the arm in CBA Design C was regulated by the cam roller, thereby facilitating the desired nonlinear force distribution. Following the enumeration of the functions performed by the primary pin and cam roller, the potential failure modes associated with these functions were identified and listed in the third column. The primary pin exhibited vulnerability to fracturing, while the cam roller displayed potential failure in rotating by the motion of the main body.

In the fourth column, the consequences of each failure mode were then considered from the perspective of the evaluated components. Analysis of the CBA concept designs revealed that failure of the primary pin or cam roller could result in the CBA's inability to distribute forces to the front and rear brakes. Following the documentation of prospective effects for each failure mode, the severity of these failures was evaluated and recorded in the fifth column. According to the severity rating table [24], all prospective failures were classified as having a very high severity because they rendered the vehicle inoperable due to the loss of its primary function. Design and material specifications of the primary pin or cam roller were identified as possible causes of these failures.

Using the occurrence rating table [24], the occurrence ranking was then determined. Design A of the CBA had a low occurrence rating of three, while Concepts B, C, and D were rated at two. In the seventh column, these occurrence ratings represented the probability of failure occurring during CBA operation. In addition to identifying the potential causes of failure, Table 1 also includes recommendations for design controls and actions for each CBA concept design. Based on design criteria and computational analysis, which were documented in the eighth column, it was possible to detect potential failures. According to the detection rating table [24], the suggested approach has a very high probability of detecting defects in CBA Designs A, B, and D. For CBA Design C, the likelihood of detection was deemed to be considerable.

Once the severity (S), occurrence (O), and detection (D) ratings were enumerated in the table, the Risk Priority Number (RPN) was calculated using equation (1) for each CBA concept design [25]. The RPN results were displayed in the table's eleventh column. CBA Design A had an RPN value of 48, CBA Design B had an RPN value of 32, CBA Design C had an RPN value of 48, and CBA Design D had an RPN value of 32. Determined and inputted into the DFMEA table were the recommended corrective actions.

Based on the calculated RPN values, the CBA concept designs were ranked in ascending order to identify the one with the lowest failure probability. CBA Design B and CBA Design D had the lowest RPN scores of 32, indicating a lower risk of failure, based on the RPN evaluation. The RPN scores for CBA Design A and CBA Design C were both 48. Due to their reduced RPN values compared to the other designs, CBA Design B and CBA Design D were deemed to be the most effective CBA concept designs.

$$RPN = O \times S \times D \quad (1)$$

3.2 Stress Analysis

In addition to the RPN analysis, a stress analysis of the primary pin was performed. This analysis was required because the primary pin played an integral role in transmitting force to the front and rear brakes. The purpose of this analysis was to determine the CBA concept design that generated the least amount of strain during actuation. Figure 4 depicts the stress contour on the primary pin for each concept design, as well as the material's yield strength, which was $2.206 \times 10^8 \text{ N/m}^2$. This value represented the utmost stress threshold that the primary pin could withstand before failure.

The analysis revealed that the utmost stress levels in each design concept did not exceed the specified stress limit. Upon comparing the individual stress values, it was determined that CBA Design C had the maximum stress, measuring $1.387 \times 10^8 \text{ N/m}^2$. The stress levels of CBA Designs A and B were lower than those of CBA Design C, measuring $1.935 \times 10^6 \text{ N/m}^2$ and $3.647 \times 10^4 \text{ N/m}^2$, respectively. CBA Design D had the lowest stress value in this analysis, with a magnitude of $6.603 \times 10^3 \text{ N/m}^2$.

Table 1: Functional DFMEA For CBA Conceptual Design

ID	Item / Function	Potential Failure Mode (Functional Failure)	Potential Effect(s) of Failure	Severity (S)	Potential Cause(s) / Mechanism(s) of Failure	Occurrence (O)	Current Design Controls - Detection	Detection (D)	RPN	Recommended Actions
CBA Design A	Primary pin - Permitted actuation to conform to the curve contour	Fracture	Failing to properly distribute forces to the front and rear brakes	8	design and material specification	3	design criteria & CAE analysis	2	48	Must adhere to design specifications and conduct durability testing
CBA Design B	Primary pin - Permitted actuation to adhere to the linear contour	Fracture	Failing to properly distribute forces to the front and rear brakes	8	design and material specification	2	design criteria & CAE analysis	2	32	Must adhere to design specifications and conduct durability testing
CBA Design C	Roller Cam – Permitted horizontal movement of the arm	Unable to rotate	Failing to properly distribute forces to the front and rear brakes	8	design and material specification	2	design criteria & CAE analysis	3	48	Must adhere to design specifications and conduct durability testing
CBA Design D	Primary pin – Permitted activation to follow the main body	Fracture	Failing to properly distribute forces to the front and rear brakes	8	design and material specification	2	design criteria & CAE analysis	2	32	Must adhere to design specifications and conduct durability testing

The design incorporating a linear slope in the tilted position in CBA Designs B and D was identified as a factor contributing to the reduced stress result. This design reduced the frictional force at the roller's contact surface with the linear slope, resulting in minimal tension on the primary pin.

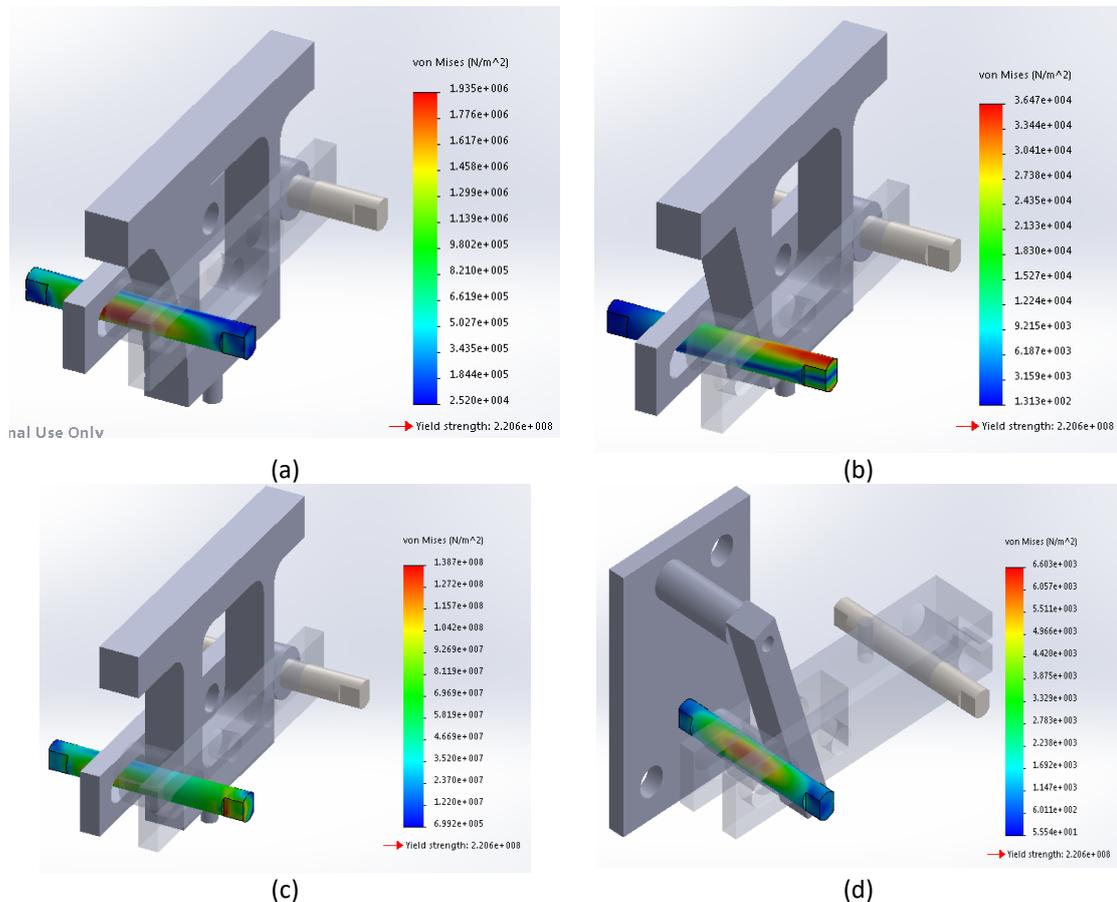


Figure 4. Stress Contour Analysis; a) CBA Design A; b) CBA Design B; c) CBA Design C; and d) CBA Design D

3.3 Concept Selection

In this section, a thorough examination of each CBA evaluation concept was conducted. All DFMEA, motion analysis, and stress analysis data were meticulously analysed. This analysis was conducted to determine the optimal CBA concept design for future CBA development. Table 2 provides a summary of the outcomes of concept evaluations conducted based on arm expansion, stress, and RPN. According to the data presented in the table, only CBA Design A and CBA Design B exhibited the capacity to horizontally extend the arm. Consequently, both of these CBA concept designs were capable of activating and distributing nonlinear braking force to the front and rear brakes. In contrast to the other CBA concept designs, CBA Design A exhibited the maximum stress levels on the primary pin. The CBA Design D, on the other hand, exhibited the lowest primary pin stress. This disparity may be attributable to the inability of the arm to expand in this particular CBA design. CBA Design B and CBA Design D earned lesser scores than CBA Design A and CBA Design C based on the RPN values. Both CBA Design B and CBA Design D obtained an RPN value of 32. In contrast, CBA Designs A and C yielded an RPN value of 48. All of these factors were considered when selecting the CBA concept design with the greatest potential.

Table 2: Summary of Concepts Evaluation

ID	Arm Expansion	Stress N/m ²	RPN
CBA Design A	Yes	1.935x10 ⁶	48
CBA Design B	Yes	3.647x10 ⁴	32

CBA Design C	No	1.387x10 ⁸	48
CBA Design D	No	6.603x10 ³	32

In this stage, concept selection is based on a weighted decision matrix, to propose the optimal CBA concept design. Table 3 presents the CBA concept design selection matrix, with the evaluated factors enumerated in the first column. CBA concept designs are evaluated using criteria such as arm expansion, stress, and RPN value. The relative importance of these criteria, known as criteria weight, is indicated in the second column on a scale from 1 to 10, with 10 representing the most essential criterion. The primary selection criteria for the CBA concept design were arm expansion and stress, as determined by an analysis of CBA concept designs. Therefore, both criteria received a score of 10, while the RPN criterion received an 8-point rating. In the third column, the performance of each CBA concept design was graded using a 5-point scale from 0 to 4. A score of 0 indicates an inadequate performance while a score of 4 indicates the greatest performance. Then, the total score for each concept design is calculated. Multiplying the grade score by the rated scale for each criterion and adding the results yields the total score. The CBA Design A received an overall score of 84, whereas CBA Design B outperformed CBA Design A with a score of 102. The CBA Design C, on the other hand, received the lowest score of 34 among the CBA concept designs. CBA Design D earned a total score of 72, placing it in third place among all other scores. As a consequence, CBA Design B was chosen as the concept design for the CBA, as it received the highest score among the other concept designs.

Table 3: Concept Selection Matrix

Concept Selection Matrix	Weight	CBA Design A	CBA Design B	CBA Design C	CBA Design D
Arm Expansion	10	4	4	0	0
Stress	10	2	3	1	4
RPN	8	3	4	3	4
Total Score		84	102	34	72

4.0 CONCLUSION

In brief, this study introduced four conceptual designs for the CBA mechanism, which were subjected to thorough evaluation using DFMEA, motion analysis, and stress analysis techniques. Based on the findings, it was decided that CBA Design B is the ideal concept design for the CBA. The conclusion was made based on a qualitative evaluation, considering the higher score obtained by CBA Design B in contrast to other designs by CBA. The CBA Design B comprises the utilization of an expanding linear contour design on its main body, which exhibits potential in providing the appropriate nonlinear force distribution across both the front and rear brakes. The present design enables the effective distribution and implementation of the desired nonlinear brake force to both the front and rear brake systems, while concurrently minimizing the probability of malfunction. Consequently, the suggested mechanism design will serve as the foundation for the future development of the CBA.

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