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IMPROVING CHASSI KART STRUCTURE CONSIDERING FATIGUE, MODAL AND STATIC ANALYSES THROUGH FINITE ELEMENT ANALYSIS

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Abstract. *Karts are simple tubular vehicles widely used since the 1960s, playing a crucial role in the development of racing drivers. This study investigates the structural fatigue and displacement behavior of a kart chassis used in professional competitions. A computationally efficient model based on a homologated chassis was developed using the finite element method. External loads were validated through practical tests using data from the Brazilian Confederation of Motorsport. Two analyses were conducted: static structural and natural frequency analysis. Numerical simulations determined stress distribution, natural frequencies, and fatigue parameters. Results contribute to the development of safer and more efficient karts. Modal analysis assessed structural integrity, showing the influence of frame tube thickness on natural frequencies and the impact of removing the anti-roll bar on displacement. This study is relevant for professional kart racing and other vehicle structural analyses. The finite element method and numerical simulations improve safety and efficiency in automotive structures.*

Keywords: *Kart, anti-roll bar, finite element method, numerical simulation, vehicle dynamics, fatigue analysis, static analysis, modal analysis.*

1. INTRODUCTION

Karts are motor vehicles that are essentially lightweight, with a tubular chassis, no suspension, 4 tires, 1 seat for the driver, 1 steering wheel, two pedals, and a power source. They were created in the mid-1950s by airplane pilots in the United States of America after World War II (FIA Karting, 2023). The first model was built using a lawnmower engine and unused metal structures. In the 1950s, karts quickly gained popularity, leading to the establishment of the first factories. With official brands in the market, karting competitions became inevitable, leading to the first races. On August 13, 1960, Brazil held its first kart race, and in 1964, the world championship brought races to Rome and Italy (Portal Kart Motor, 2022).

Competitions were crucial for the technological advancement of karting. Teams started using multiple chassis and engines to adjust the vehicle's stiffness or power for different tracks or countries. Furthermore, adjustable parameters were created within the chassis to allow teams to make changes to the dynamic characteristics more quickly.

The automotive industry of the time served as a basis and inspiration for these adjustment parameters. Despite not having a suspension, concepts from vehicle dynamics related to load transfer were applied in a similar way (Piazza, 2022). Studies focusing on lateral and longitudinal load transfer, control of stiffness, and body roll were applied to develop kart dynamics.

The anti-roll bar, according to Milliken (1995), is responsible for vertically connecting the left and right wheels of the same axle, reducing body roll. During a turn, the anti-roll bar generates dynamic reactions, rotations, and deflections that are transmitted from one wheel to the other, creating a physical dependency that increases chassis stiffness. It is worth noting that this bar only affects lateral movements, where the wheels have opposite movements, and it is useless for longitudinal movements such as acceleration and braking, where the wheels either move up or down together relative to the chassis.

The stiffness and roll of the chassis can be adjusted by adding or removing the anti-roll bar. The attachment location, material, and geometry of the bar directly affect chassis stiffness. Therefore, an analytical study is necessary for teams or manufacturers to determine how stiffness will be altered in order to choose the best bar for each race (Carvalho, 2004).

Currently sold anti-roll bars for karts often do not provide data on stiffness, deformation, and fatigue. One way to reduce costs and practical testing is by using the finite element method (FEM) (Mascia, 2006). Originating around the 1950s, it has been widely used, especially with computational advancements, according to Sabat (2021). The main point is to discretize the structure into elements that are analyzed as if they were springs, where an external force is equal to the stiffness matrix multiplied by the deformation field of the element.

Thus, racing teams can use structural analysis with discretized geometry to determine the best adjustment for each track condition. Calculation of stress and deformation fields provides results of deformation and yield stress related to material integrity. Natural frequencies or resonant frequencies can also be calculated using this theory.

2. VEHICLE CAR DYNAMICS

Vehicle dynamics encompasses the analysis of the vehicle and its components' motion in response to external forces. These forces can arise from various sources, including track irregularities like bumps, potholes, and inclines, as well as driver-induced actions during cornering, acceleration, or braking. The study of vehicle dynamics can be approached through two main methods: dynamic analyses, which view the vehicle as a collection of moving mass points, and static analyses, which focus on momentary forces (Cossa, 2017).

The investigations within this field can be classified into two categories: lateral and vertical motions. The examination of vertical dynamics is concerned with controlling the vibrations between the suspended and unsuspended masses. In the context of a kart, this involves analyzing the deflection of the axle and chassis, as well as vibration characteristics. Lateral dynamics, on the other hand, pertain to load transfer in response to external forces and the resulting dynamic behavior of the vehicle. This includes phenomena such as body roll, understeer or oversteer tendencies, and passenger comfort. In both cases, the equations for force summation along the chassis are utilized to determine the center of mass and the associated reactions, as outlined by Gillespie (1992).

2.1 Anti roll bar

Anti-roll systems serve two primary purposes: mitigating body roll and providing adjustable stiffness on one side compared to the other (Seward, 2017). While roll is not excessively detrimental in vehicles with low centers of gravity like karts, it can induce a force that affects the tire's contact angle with the ground, commonly referred to as camber, thereby reducing tire efficiency.

Due to minimal roll, the ARB (Anti-Roll Bar) of a kart has limited influence on altering the tire's contact angle with the ground. However, it significantly affects lateral load transfer per axle, consequently impacting the vehicle's behavior. By adjusting the stiffness at the front or rear, the vehicle's handling characteristics can be modified. Front stiffness can be adjusted by adding or repositioning the front anti-roll bar, while rear stiffness can be modified by removing the front bar. As the lateral load transfer remains constant, removing the front bar makes the rear comparatively stiffer.

The height of the center of gravity and its management directly influences tire efficiency. Milliken (1995) demonstrates the non-linear relationship between lateral force gain and vertical loading in tires. Consequently, the inner tires, which experience a decrease in vertical load, exert a more substantial influence on overall lateral acceleration compared to the outer tires. This emphasizes the importance of reducing lateral load transfer in order to achieve higher lateral acceleration.

3. STRUCTURE MODELING AND SIMULATION PARAMETERS

A subset of CAE is CAD (Computer-Aided Design). The advancement of computer-based drawings enables improved and expedited visualization of the structure, along with easy parameter modifications such as thickness, angle, or length of the geometry (Shigley, 2005). Additionally, other properties like center of gravity, mass, mass moments of inertia, and specific distances within the structure can be quickly verified or calculated, as stated by Cossa (2017).

The CAD model of the vehicle was developed with simplifications of non-essential components to conserve computational resources and streamline the proposed analyses. Figure X depicts a representation of the evaluated elements.

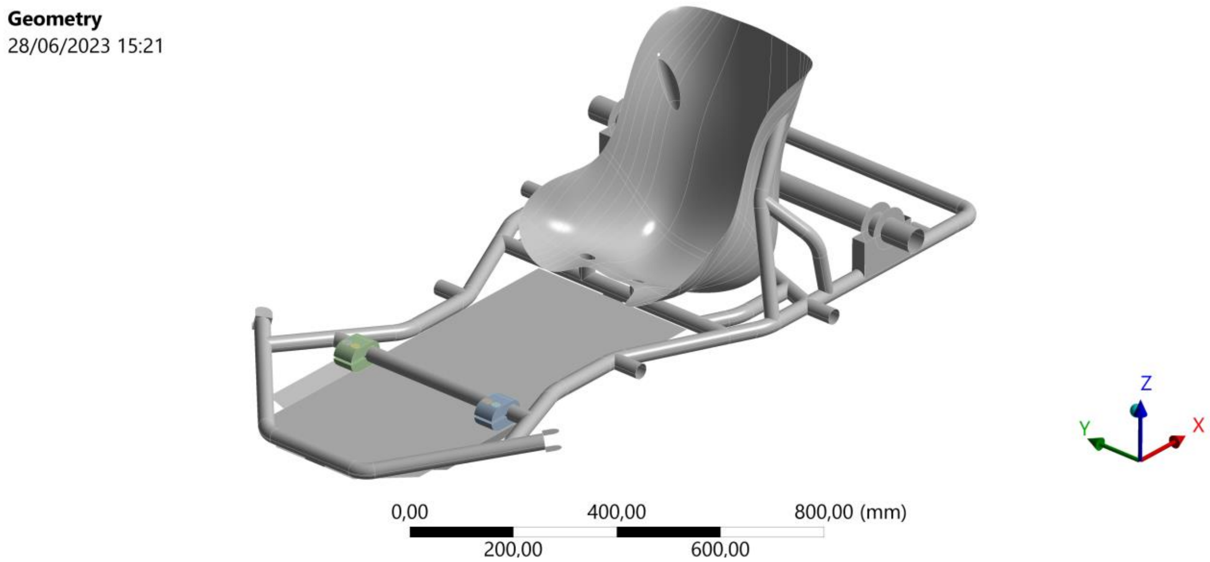


Figure 1 - Chassis

The numerical simulation requires a chassis modeled according to those used in competition for the results to be consistent with reality. Kart manufacturers make changes to the thickness of the chassis tubes from one track to another, as well as alter the material of certain components such as the ARB. Therefore, modeling was performed for 4 cases, varying the thickness and material of the ARB while maintaining the geometry specified by the CBA (Confederação Brasileira de Automobilismo) for chassis homologation. The analyzed chassis is based on the model from the Brazilian manufacturer Thunder, located in Paulínea, São Paulo, from the year 2022 (Figure 2).

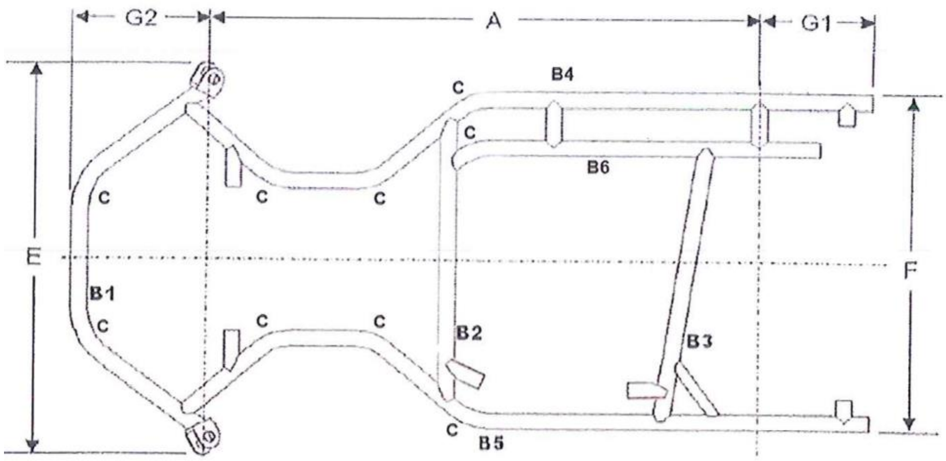


Figure 2 - Approval Drawing

To evaluate the structural performance and understand how material and geometric variations impact the stiffness of the structure, static analyses were performed using monotonic and cyclic loading. These analyses were based on parameters obtained under the highest-demand condition. For the static simulation, a reverse load with a magnitude of 270 N was applied at the anchor points of the front wheels, aiming to replicate a twisting condition similar to the load transfer experienced during cornering on a track (Figure 3).

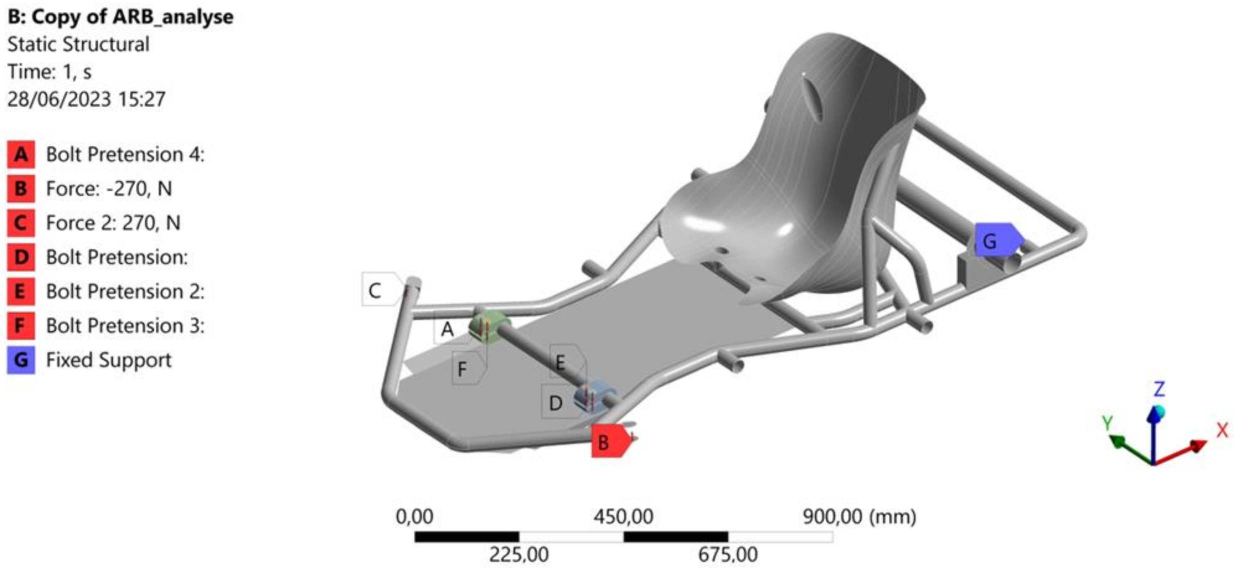


Figure 3 - Boundary Conditions

For the frequency study of the structure, a free modal analysis was performed to evaluate the behavior of the structure under the effect of stiffness variation due to changes in the ARB. Additionally, a CAD model analysis was conducted to observe the presence of rigid body behaviors associated with the first 6 modes of vibration (Salgado, 2012).

$$f = w/2\pi \quad (1)$$

$$w = \sqrt{(k/m)} \quad (2)$$

$$f = \sqrt{(k/m)}/2\pi \quad (3)$$

Where the w is the angular frequency of the oscillation (radians or seconds), f is the natural frequency, k is the spring constant for the spring, m is the mass of the structure.

In the fatigue study, the S-N model was adopted for high-cycle fatigue at the most critical points of the structure. The proposed loading was obtained from lateral acceleration data, which directly influences the load transfer. For data acquisition, a Mychrons Generation 5 data acquisition system was used. The device was fixed to the vehicle's steering wheel to obtain the maximum lateral acceleration for each of the 10 laps. The test was performed using new tires, only the necessary amount of fuel, and without additional weight to ensure only the minimum weight of the category.

Telemetry sensors need to be fixed near the vehicle's center of gravity. The distance between the acquisition system and the CG results in a lever arm that generates reading errors. However, since the kart does not have suspension and due to this factor, it exhibits high vibrations, sensors directly fixed to the chassis showed noise that hinders precise analysis. The application of filtering to linearize the graphs is essential, but overly filtered data does not represent the peaks of lateral acceleration. Furthermore, the analysis focuses on maximum acceleration, disregarding the movement around the ground plane, which is affected by steering wheel rotation in curves. Therefore, the fixation was done on the steering wheel as the steering system has polymer bushings that absorb vibrations, reducing noise in the readings.

All analyses were performed using nonlinear contact conditions at the connection points of the ARB with the chassis, using intermediate linking structures. The "normal Lagrange" formulation was used in the elements, which does not allow mesh penetration. This formulation has higher computational cost but provides high numerical accuracy.

For the material variation study, the most used compositions for this purpose were employed. Table 1 presents the properties of each material.

Table 1 – Materials Mechanical Properties

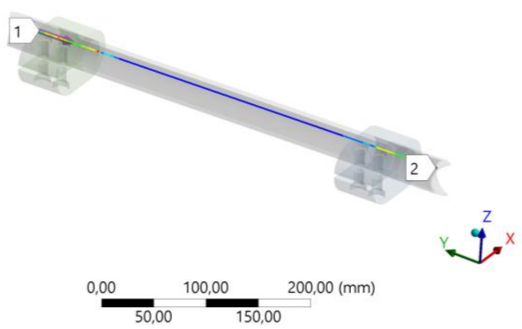
Properties	**Structural Steel**	**PVC**	**Carbon Fiber**	**Al 6061-T6**
E [GPa]	200	2.86	59.16	69.04
v	0.3	0.4	0.3	0.33
Density [Kg m^-3]	7850	1392	1451	2713
Yield strength [MPa]	250	46.71	510	259.2

4. RESULTS AND DISCUSSION

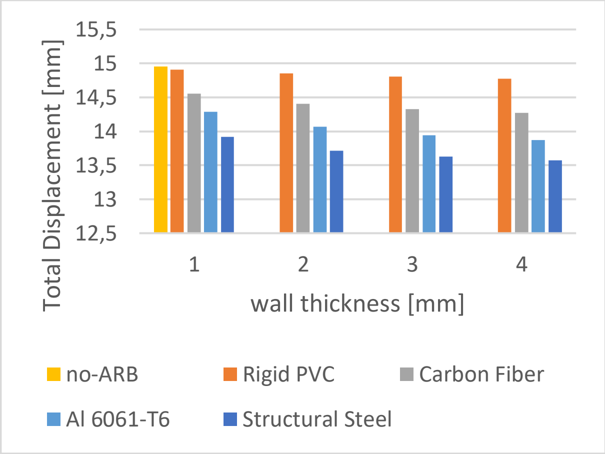
The structural static analysis had two main analysis parameters, with the first one being the stress field of the chassis, analyzed through the equivalent von Mises stress. By using graphs to compare different materials, the non-homogeneity of the Anti-Roll Bar (ARB) is notable, with variations in materials and/or thickness within the same material. The steel bar exhibited the highest variation, 20MPa, in the stress field, varying thickness among the tested materials (steel, aluminum, polymer, and carbon fiber). The aluminum bar had the second highest variation, approximately 5MPa, although the 1mm thickness showed a more sensitive behavior at the contact points with the bite plates. It is worth noting that the aluminum ARB had a lower stress field throughout its length.

The material with the least variation in the stress field due to thickness variation was the polymer, in this case, PVC. The second material with the least variation was carbon fiber, although it had the highest variation where the bar contacts the bite plates.

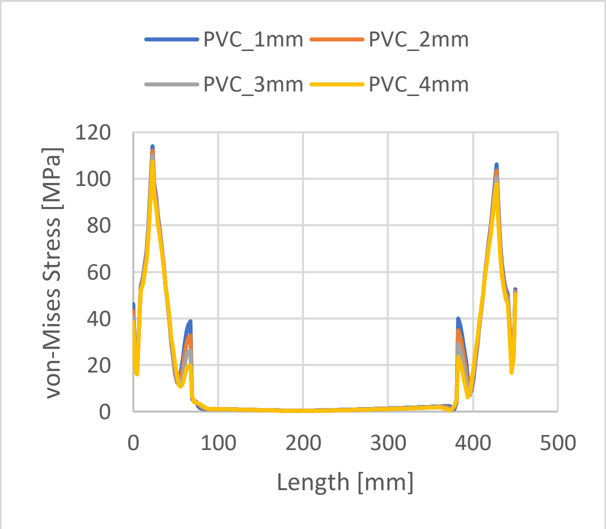
The second parameter analyzed in the static analysis was the total deformation. The highest deformation was obtained in the simulation without the ARB, followed by the PVC and carbon fiber bars, both ranging between 14.5 and 15mm for 1mm thickness. The lowest deformation, between 13.5 and 14mm, was obtained in the simulation with the steel bar, followed by the aluminum bar with 4mm thickness.



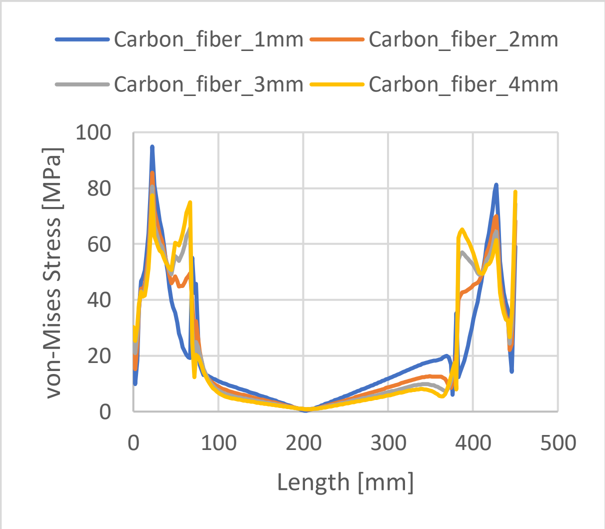
a) Von-Mises Stress analyses path



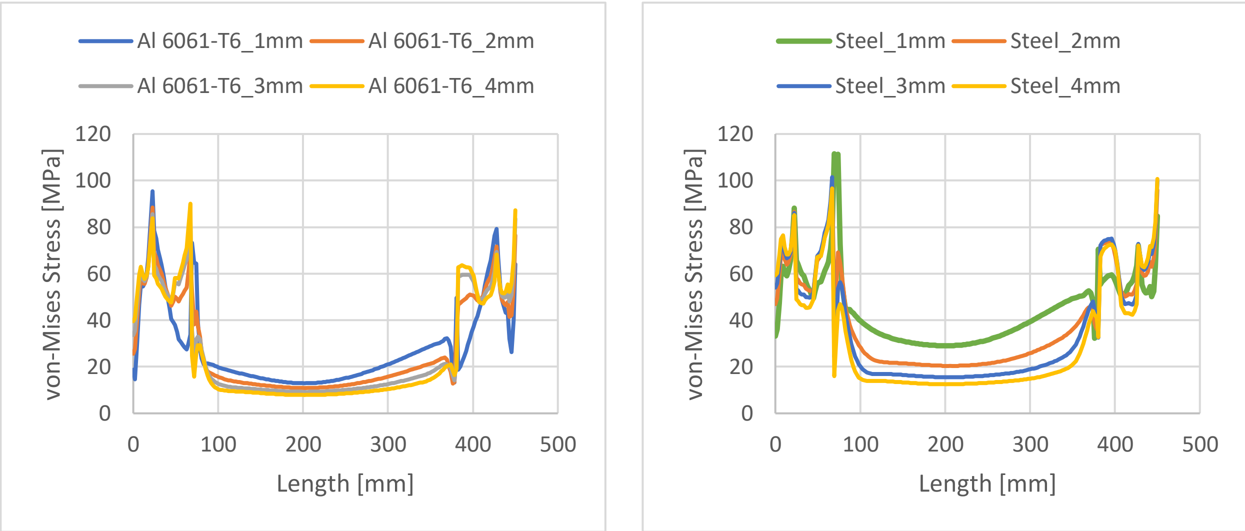
b) Comparative displacement x wall thickness



c) PVC



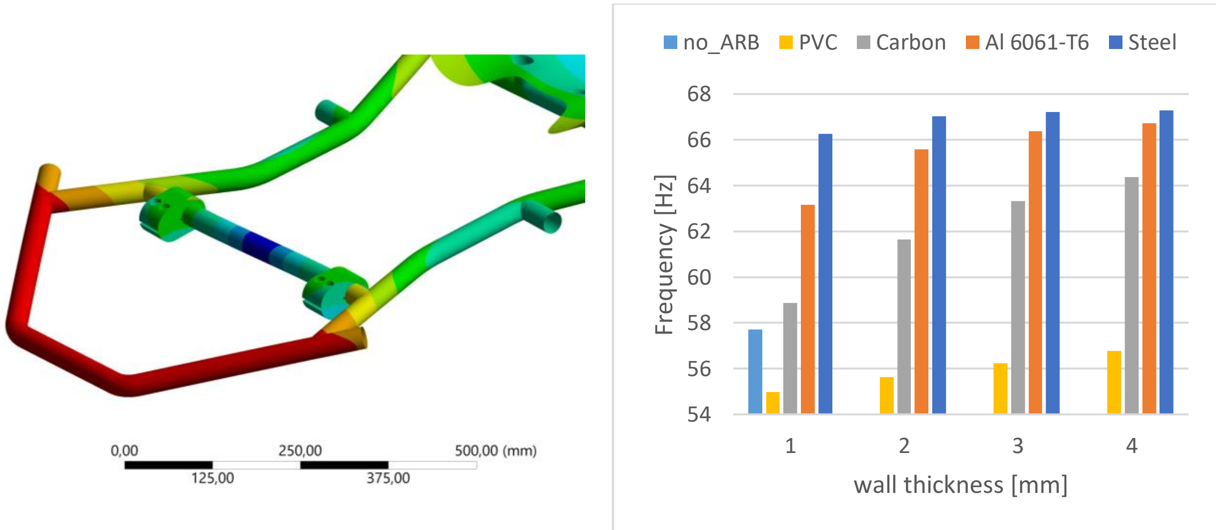
d) Carbon Fiber



e) Al 6061-T6 f) Structural Steel

Figure 4. ARB material Comparative analysis

The initial modal analysis conducted aimed to verify the structural integrity through free vibration. Upon confirming that the first six natural frequencies converged to zero, a modal analysis with imposed boundary conditions was performed. The obtained natural frequencies were scrutinized within the frequency range of 54 to 68Hz due to its heightened variability. Notably, the bars with greater rigidity, characterized by thicker steel sections, exhibited the highest natural frequencies, whereas the less rigid bars displayed natural frequencies up to 17Hz lower.

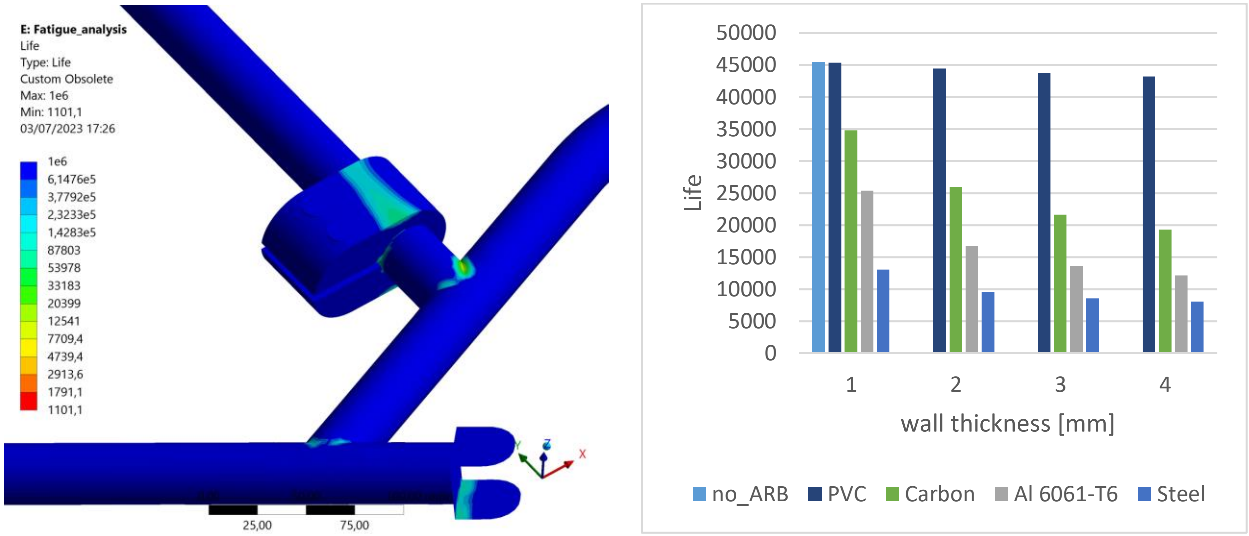


a) Modal analyses in 54 to 68 Hz Range b) Comparative Frequency x wall thickness

Figure 5. Modal analyses

The fatigue analysis resulted in a reduced life expectancy for the stiffer bars. Increased bar rigidity led to higher concentrations of localized stress, ultimately resulting in fatigue failure (Branco, 1999). However, it is worth noting that even the steel bar with a wall thickness of 4mm still exhibits a life expectancy of approximately 8,000 load cycles, indicating it falls within the realm of high-cycle fatigue.

The areas most affected by fatigue were observed at the connections of the anti-roll bar. However, due to the imposed boundary conditions, the junction of the tubes supporting the anti-roll bar was the most impacted area in terms of fatigue.



a) Fatigue spots

b) Comparative Life x wall thickness

Figure 6. Fatigue analyses

The fatigue analysis was conducted to better characterize the anti-roll bar with the different thicknesses and materials considered. An S-N plot was created, illustrating the relationship between the stress field obtained from the static structural analysis and the number of cycles obtained from the fatigue analysis.

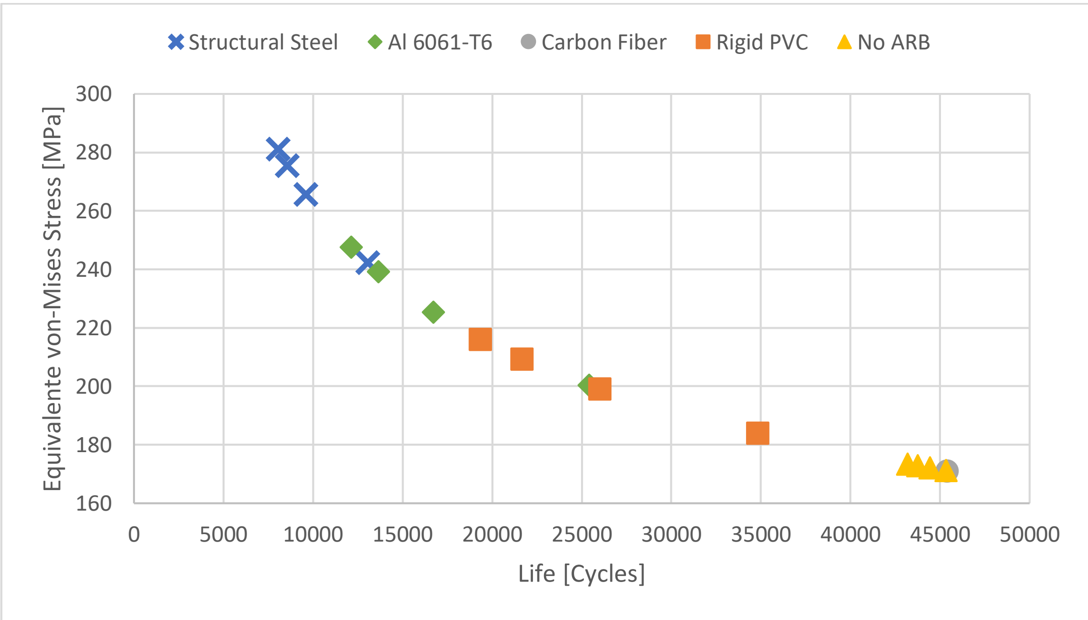


Figure 7. S-N plot for different materials and thicknesses of ARB

5. CONCLUSIONS

The present work aimed to analyze the interference of the anti-roll bar (ARB) of a go-kart using the Finite Element Method (FEM). The modeling presented difficulties due to nonlinear contacts, modal analysis with multiple bodies, and the limited literature on the subject. During the simulations with the approved chassis, unexpected behaviors were observed due to the low rigidity of the model. Therefore, the modeling needs to take into account the structural components such as the seat, floor, axle, and their fasteners. With a model closer to a real go-kart, the results are satisfactory and behave as expected. The static structural analysis highlights the interference of material and geometry changes on the ARB. Stiffer bars resulted in lower displacement, as well as stress fields with greater variation for different thicknesses. The modal analysis yielded higher frequencies for the stiffer bars. Finally, fatigue simulations indicated a shorter lifespan for the stiffer ARBs due to higher local stresses. In conclusion, the proposed modeling and analysis methodology allows obtaining satisfactory results, as the interference of the ARB can be determined for a go-kart chassis. Through the conducted studies and analyses, the behavior of the chassis with the added bar becomes more predictable, including the predictability of the chassis' life and natural frequencies. Thus, track engineers and designers can employ the proposed method and conduct fewer empirical tests, reducing operational costs and increasing the accuracy of real tests.

6. ACKNOWLEDGMENTS

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