Effects of Geometry Design Parameters on the Fatigue Failure of a Drive Axle Housing using Finite Element Analysis

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ABSTRACT

The current paper investigates the effects of geometric design parameters on the fatigue failure of the drive axle housing using the Finite Element Method (FEM). The study examines the effects of various factors on the fatigue life of the drive axle housing, such as axle housing wall thickness, housing cross-sectional rounding radius, and rounding radius of the central part of the housing. Based on the known material properties and dynamic loads, a CAD/FEM model of the drive axle housing was developed, and a structural analysis was carried out. Based on the results of the structural analysis, critical places on the housing were determined, and fatigue analysis and lifetime prediction were performed. Through a series of simulations, the study reveals that increasing housing wall thickness can significantly improve fatigue performance. Similarly, increasing the rounding radius at the housing cross-section, as well as the rounding radius at the central part of the housing can also lead to improved fatigue performance. However, the effect of increasing the value of these two radii is not as significant as the effect of the wall thickness. These findings give useful information regarding the design and manufacture of drive axle housings for vehicles, intending to reduce the likelihood of fatigue failure.

Keywords-drive axle housing; fatigue failure; finite element analysis

I. INTRODUCTION

During the vehicle service life, dynamic forces caused by road roughness create dynamic stresses that lead to fatigue failure of the drive axle housing. Therefore, it is vital that the drive axle housing resists fatigue failure for its intended service life [1]. Also, it is necessary that the strength and stiffness of the drive axle housing meets the specified service requirements [2]. Due to its importance in the vehicle, the drive axle housing is a constant topic of research, especially from the aspect of fatigue failure analysis. It is stated in [3] that the welding procedures affect the occurrence of fatigue cracks in the drive axle housing of heavy trucks. Based on fracture mechanics, authors in [4] analyzed the occurrence of fatigue cracks on the drive axle housing of a crane truck. The four-point bending fatigue test of the drive axle housing assembly using the Finite Element (FE)-integrated fatigue analysis methodology was simulated in [5]. The presented technique is based on the local stress and strain approach in combination with two critical plane damage parameters. Authors in [6] studied the drive axle housing fracture of a mining dump truck based on the load spectrum. In order to determine the causes that affect the drive axle housing dynamic stress, the road slope, any uneven load and eccentricity are analyzed using the finite element method. Authors [7] performed deterministic and probabilistic fatigue life calculations of a damaged welded joint in the construction of the rear axle of a trolleybus. In their study, they state that the main purpose of the calculation was to determine whether in-service failure could be predicted (and prevented) during the design phase and what was their main cause. Authors in [8] studied the dynamic response and fatigue life prediction of a vehicle system under a random road spectrum and analyzed the dynamic stress magnitude and fatigue life in the resonant frequency region. Authors in [9] used ABAQUS software to analyze the dynamic and static characteristics and fatigue analysis of car drive axle housing under sinusoidal load spectrum, obtain plots of the location and life distribution of the fracture zone, and propose improvement plans.

Authors in [10] took the drive axle housing of a light truck as the research object, and chose the design parameters, permitted stress, and displacement with least weight as the optimization goal. Authors in [11] analyzed the dynamic characteristics and fatigue of the drive axle housing and carried out a lightweight optimization design to verify the optimized drive shaft housing. Authors in [12] presented a reliability analysis method based on the Monte Carlo technique by studying the optimization scheme of the drive axle housing of off-road vehicles. Based on this, lightweight design was carried out and the weight of the drive axle housing was reduced by 12.48%. Authors in [13] carried out Six Sigma multi-objective lightweight drive axle housing design, studied the influence of drive axle housing wall thickness on its performance using entropy weight methods and TOPSIS, and combined RBF and NSGA-II algorithms to design a multi-purpose lightweight drive axle housing, which significantly improved performance. To study the vertical fatigue of the drive axle housing, authors in [14] proposed a seven degree of freedom dynamic model to predict fatigue failure under dynamic load and presented an optimization scheme based on this.

Furthermore, numerous studies have examined the effects of geometric design parameters on the structural failure due to fatigue [15-18]. The abovementioned research was mainly aimed at examining the influence of various factors on the service life of the drive axle housing, such as driving conditions, vehicle load, material properties, and axle housing manufacturing technology. The aim of this paper is to investigate the influence of geometric design parameters on the fatigue failure of the drive axle housing using the FEM. The design parameters that were taken into account during the analysis are the thickness of the axle housing wall, the rounding radius at the cross section of the axle housing, and the rounding radius at the central part of the axle housing.

II. DEVELOPMENT OF THE CAD/FEM MODEL

The CATIA V5 software package was used during the development of the CAD/FEM model of the drive axle housing. After the CAD model of the housing was formed (Figure 1), the material of the housing (S460N) with the mechanical properties shown in Table I was defined.

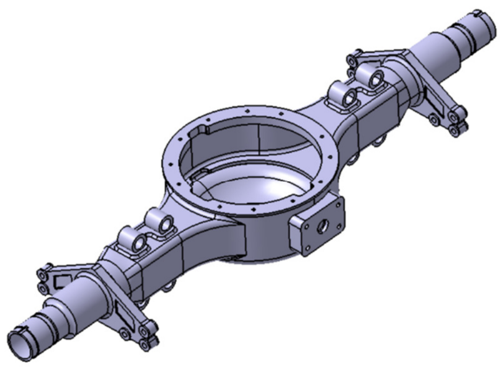

Fig. 1. CAD model of the drive axle housing,

TABLE I. MECHANICAL PROPERTIES OF HOUSING MATERIAL S460N

Young's modulus of elasticity	E	208.5 GPa
Yield strength	S_y	497.5 MPa
Poisson's coefficient	ν	0.3
Brinell Hardness number	HB	190
Shear modulus	G	73 GPa
Tensile strength	S_{ut}	629.9 MPa
Strain at brake point	ε_{max}	26.8 %
Shear strength	SS	390 MPa
Density	ρ	7860 kg/m^3

After the CAD model of the housing was formed, FEM modeling was performed in the Generative Structural Analysis module. The first step in the FEM modeling is discretization and selection of finite elements, where FEs of the parabolic type (TE10) tetrahedron were used. The size of the element was 9 mm with an absolute sag value of 1.8 mm.

After discretization, it is necessary to define the load acting on the drive axle housing. The drive axle housing is loaded with bending stress due to the weight of the truck with the trailer. The intensity of the load is defined according to the legal requirements and the axle configuration of the truck whose drive axle housing is the subject of analysis. According to regulations [19], maximum load of the drive axle, i.e. the drive axle housing in which the drive axle is located, must not exceed 113 kN. Therefore, a load of 56.5 kN was applied in the form of concentrated axial forces at the places where vehicle pneumatic suspension system is attached (Figure 2).

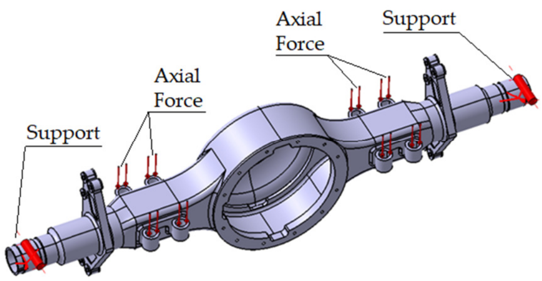

Fig. 2. Defining of boundary and loading conditions.

After defining the load, the boundary conditions are defined (housing supports). The housing is supported on the places where the bearings are located. It was necessary to define the previously created virtual part using the Rigid Virtual Part command. Then, using the Pivot command, boundary conditions were defined in such a way that rotation of the housing around the z axis was allowed. After the FEM modeling of the drive axle housing in the CATIA V5 software package, structural analysis was performed for the given load. During the structural analysis, the von Mises stress values generated on the housing were monitored, along with the displacement values (Figures 3 and 4).

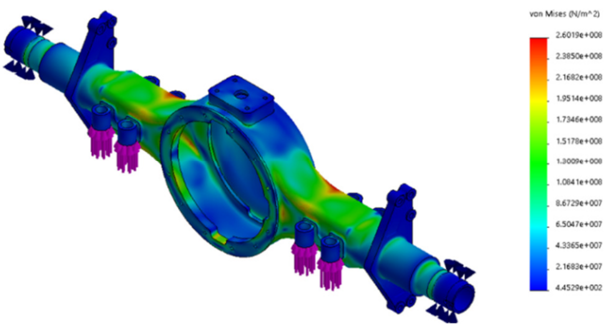

Fig. 3. Von Mises stress distribution.

As can be seen from Figure 3, the von Mises stresses are mainly distributed in the places of the hollow square cross-section, and at the transitions towards the middle part of the drive axle housing where final drive is located. The extreme value of the von Mises stress is 260.19 MPa and is located exactly at the mentioned place of the housing, which is exposed to tension. The stress values that occur at the walls of the hollow square cross-section are in the range of 90 MPa to 155 MPa, depending on the distance from the point of action of the load. The smallest stresses, as expected, occur at the points of support and are negligible. It can be seen from Figure 4 that the largest displacements of 3.12 mm, as expected, occur towards the middle of the drive axle housing. Moving towards the ends of the housing, i.e. towards the support places, the displacements decrease.

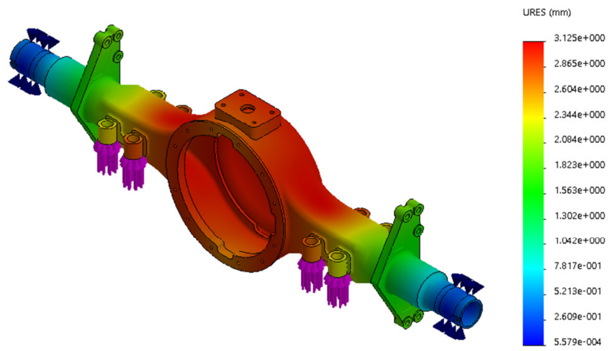

Fig. 4. Displacement distribution.

III. FATIGUE LIFETIME PREDICTION

Fatigue analysis and fatigue lifetime prediction of the drive axle housing were performed in the Solidworks software package, based on the previously performed structural analysis. The estimate of the fatigue limit S_e' is given as:

$$S_e' = 0.504\, S_{ut} \quad (1)$$

for steels with tensile strength up to 1400 MPa [20]. This represents fatigue strength at 10^6 cycles and above. To predict the axle housing fatigue life in the range of 10^5-10^6 cycles, the S–N curve of the housing material was evaluated using a practical method [21] with data obtained from tensile testing. S_e' represents the fatigue limit of ideal laboratory specimens. To predict the fatigue limit S_e of actual mechanical component, S_e' must be multiplied by several correction factors that represent the influences of design, manufacturing, and environment on fatigue strength [22]. S_e is defined as:

$$S_e = k_a k_b k_c k_d k_e S_e' \quad (2)$$

where k_a represents the surface factor depending on the surface treatment. It is defined as:

$$k_a = a\, S_{ut}^b \quad (3)$$

Since the surface roughness of the shell is similar to hot rolled steel sheet after hot stamping, the recommended values are a = 57.7 and b = -0.718 [23], so the value of the factor k_a is 0.564 for S_{ut} = 629.9 MPa. In addition, the housing surfaces are subjected to steel shot blasting to increase housing lifespan. This process may increase lifespan by 70% [21]. Therefore, in the fatigue analysis, the value for k_a used is 0.959. For non-round cross sections, the size factor k_b can be taken as 0.75 for values of the cross-section depth h greater than 50 mm. The load factor k_c is 1 for the bending load. The temperature factor k_d is 1 for the ambient temperature range of T = 0–250°C [24]. Static FEM analysis showed that there are areas of stress concentration at certain parts of the housing. Therefore, apart from the aforementioned correction factors, the correction factor for the fatigue strength k_e should be taken into account. This correction factor is taken through the static stress concentration factor K_t, which is related to the fatigue stress concentration factor K_f. Therefore, k_e is calculated as:

$$k_e = \frac{1}{K_f} \quad (4)$$

It can be assumed that K_f is equal to K_t [23]. Due to the dimensions and complexity of the housing shape, K_t cannot be derived from the data in the literature but is defined as:

$$K_t = \frac{\sigma_p}{\sigma_n} \tag{5}$$

where σ_p is the maximum stress at the stress concentration point, and σ_n is the nominal stress that would have been present if stress concentration had not occurred [21, 25]. The stress σ_p was determined by the previous FEM analysis and is calculated as 260.19 MPa, while the stress σ_n is calculated by considering the drive axle housing as a simple beam with a uniform cross-section box profile loaded by pure bending. So, it is defined as:

$$\sigma_n = \frac{M}{W_x} \tag{6}$$

where M is the bending moment, and W_x is the section modulus of housing cross-section. Therefore, based on the nominal stress value of σ_n =305 MPa, we get $K_t \approx K_f = 1.181$ and $k_e = 0.846$. With regard to the correction factors, the *S-N* curve is defined in Solidworks (Figure 5).

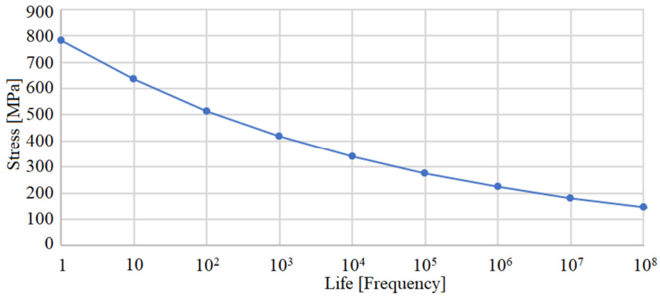

Fig. 5. S-N curve of S460N.

The S-N curve shows that the stress amplitude of the element depends on the number of cycles during its lifespan. The number of cycles is required as input data so that the fatigue analysis of the drive axle housing can be performed. In addition to the S-N curve, it is necessary to define the number of cycles to which the housing is exposed, as well as the loading pattern. The drive axle housing bore load history is a non-zero mean random load. The Goodman mean stress theory is used to correct the non-equal amplitude stress and set the type of analysis to stress life [26]. The number of cycles is set to 109 in the safety factor analysis module [2].

IV. RESULTS

The results of the carried out fatigue analysis of the initial design of the drive axle housing are presented in Figure 6. The probability of the initial crack occurring at the highest stress point is shown in Figure 6(a). The number of cycles at which the crack appears is shown in Figure 6(b) (61936 cycles). Based on the results of the fatigue analysis of the initial design of the drive axle housing and the observed fact that the hollow square cross-section is the critical point of construction, measures were taken to extend the lifespan of the drive axle housing.

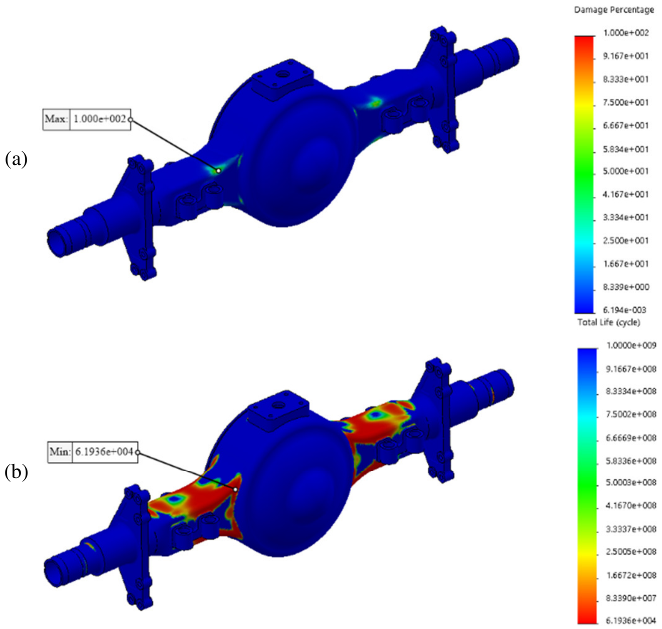

Fig. 6. Initial design of drive axle housing: (a) probability of initial crack occurrence, (b) number of cycles until fatigue failure occurs.

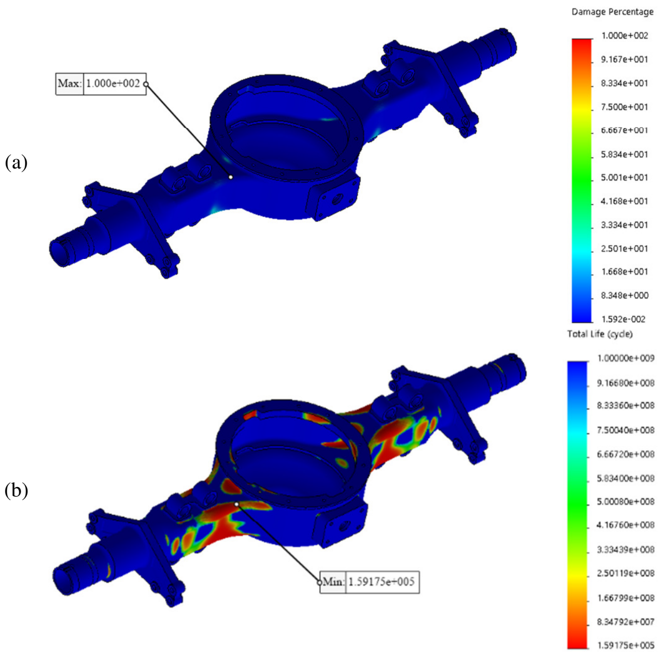

Fig. 7. Design of drive axle housing with increased wall thickness: (a) probability of initial crack occurrence, (b) number of cycles until fatigue failure occurs.

The first modification of the existing structure, in order to extend the lifespan of the drive axle housing, is to increase the thickness of the wall of the hollow square cross-section, which represents a critical place on the structure in terms of lifespan. The wall thickness was increased from 8 mm to 9 mm, and the results are presented in Figure 7. The second modification of the existing structure is to increase the rounding radius of the hollow square cross-section of the housing. The inner and outer rounding radii are increased by the same value, in order to maintain the same cross-sectional wall thickness. The inner rounding radius was increased from 10 mm to 13 mm, while the outer radius increased from 18 mm to 21 mm. The results are presented in Figure 8.

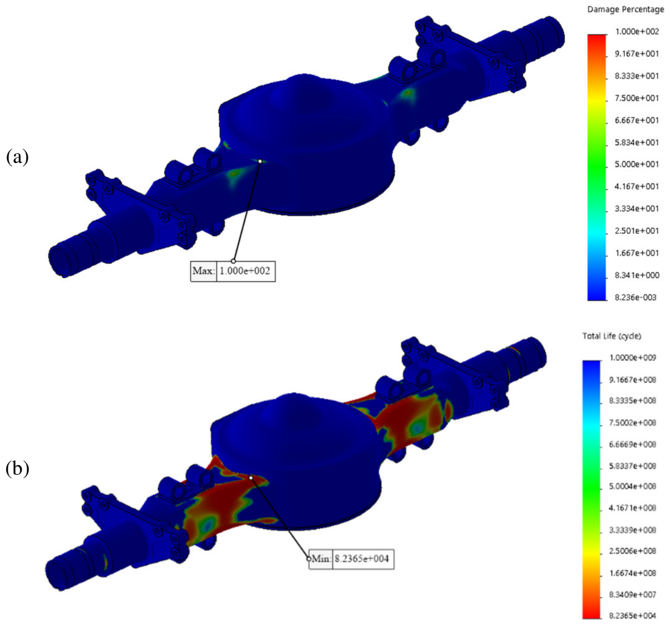

Fig. 8. Design of drive axle housing with increased rounding radius of the housing cross-section: (a) probability of initial crack occurrence, (b) number of cycles until fatigue failure occurs.

TABLE II. RESULTS OF STRUCTURAL AND FATIGUE ANALYSIS

Design	Von Mises stress (MPa)	Percentage change (%)	Displacement (mm)	Percentage change (%)	Number of cycles (-)	Percentage change (%)
Initial	260.19	-	3.12	-	61936	-
With increased wall thickness	231.17	-11.2	2.91	-6.7	159175	157
With increased rounding radius of the axle housing cross-section	254.43	-2.2	3.14	0.6	82365	33
With increased rounding radius of the central part of the axle housing	254.04	-2.4	2.99	-4.2	81807	32

The third modification of the existing structure, in order to extend the lifespan of the drive axle housing, is to increase the rounding radius of the central part of the housing. The inner and outer radii are increased by the same value, in order to maintain the same cross-sectional wall thickness. The inner radius was increased from 222 mm to 252 mm, while the outer radius was increased from 230 mm to 260 mm. The results are presented in Figure 9. The results of the structural and fatigue analysis of the initial design of the drive axle housing, along with the modified designs of axle housing, are shown in Table II.

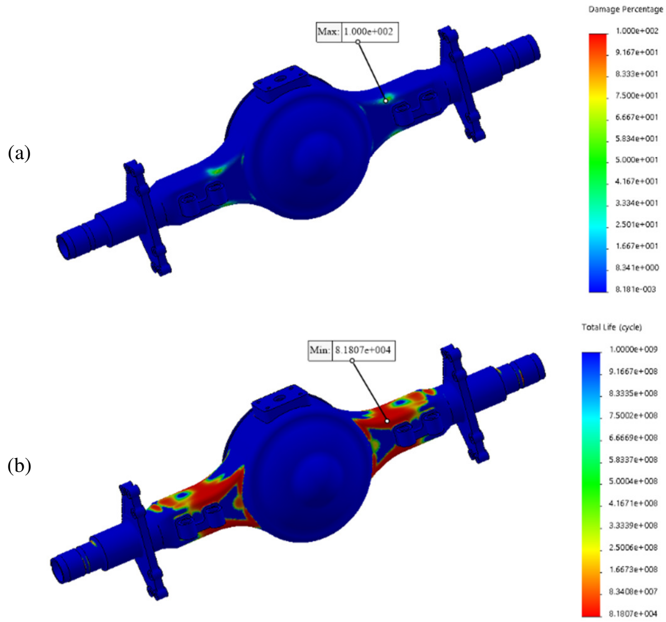

Fig. 9. Design of drive axle housing with increased rounding radius of the central part of the housing: (a) probability of initial crack occurrence, (b) number of cycles until fatigue failure occurs.

V. DISCUSSION

The structural analysis of the initial design of the drive axle housing showed critical locations where fatigue failure occurs. That critical place is at the transition from the hollow square cross-section to the central part of the axle housing where the final drive is located, on the side of housing that is exposed to tension. The number of cycles that the specified location can withstand before the first crack appears is 61936. In order to extend the lifespan of the axle housing, certain geometric changes were made.

The simplest way to increase fatigue strength is to increase the wall thickness of the axle housing. When increasing wall thickness by 1 mm, the value of the maximum stress decreased from 260.19 MPa to 231.17 MPa, representing a decrease of 11.2%. There was also a reduction in displacement from 3.12 mm to 2.91 mm, which represents a reduction of 6.7%. This greatly contributed to the increased lifespan of the structure from the initial 61936 to 159175 cycles, which represents an increase of 157%. On the other hand, the increase in the axle housing wall thickness causes an unnecessary increase in the weight of the housing, from 166.58 kg to 169.07 kg, which represents an increase of 1.5%. An alternative to this is to reduce the stress concentration through geometric redesign. Smoother transition geometry can offer increased lifespan without additional weight.

Looking at the results of the structural and fatigue analysis of the design with an increased rounding radius of the axle housing cross-section, a change of maximum stress from 260.19 MPa to 254.43 MPa, which represents a decrease of 2.2%, can be noticed. On the other hand, there was a slight increase in displacement from 3.12 mm to 3.14 mm (0.6%). By increasing the rounding radius of the cross-section, the lifespan of the structure is increased from the initial 61936 to 82365 cycles (33% increase), while the weight of the axle housing remains unchanged.

Looking at the results of the structural and fatigue analysis of the design with an increased rounding radius of the central part of axle housing, similar trends as in the previous case can be noticed. There is a 2.4% decrease of maximum stress from 260.19 MPa to 254.04 MPa. On the other hand, unlike the previous case, there is a reduction in displacement from 3.12 mm to 2.99 mm (4.2%). Similar to the previous case, by increasing the rounding radius of the central part of the axle housing, the lifespan of the structure is increased from the initial 61936 to 81807 cycles, representing an increase of 32%, while the weight of the axle housing remains unchanged.

VI. CONCLUSION

Analysis of the geometric design parameters for the fatigue failure of the drive axle housing led to the following conclusions:

- Increasing the wall thickness significantly reduces the stress level that occurs at the axle housing, especially in critical areas with maximal loads. This contributes to increased lifespan of the housing and improves fatigue strength, but also increases the weight of the housing.
- Increasing the rounding radius of the cross-section of the axle housing, the stress concentration is reduced. This results in an increased lifespan of the axle housing without increasing its weight.
- Increasing the rounding radius of the central part of the axle housing positively affects the reduction of stress concentration, which achieves a better distribution of stress through the structure. This ultimately results in an increased service life of the housing without increasing its weight.

As a result of this research, designers and engineers in the automotive industry are equipped with evidence-based guidelines for optimizing driveshaft housing design. By applying the knowledge gained from this study, manufacturers can extend the lifespan and the reliability of the axle housing, consequently improving the overall performance, safety and longevity of the vehicle.

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