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Fatigue life evalution of a bus charging door bracket

Bir otobüs şarj kapaği braketinin yorulma ömrü değerlendirmesi

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Abstract

This study presents a comprehensive evaluation of the fatigue performance of two different bracket designs used in the charging door mechanism of an M3-class electric bus—one made from Aluminum 6061-T6 and the other from ST52 structural steel. Both brackets were subjected to constant-amplitude cyclic loads derived from real service data. Fatigue life predictions were conducted using finite element analysis (FEA) and two stress-based approaches: the Soderberg criterion and the Smith-Watson-Topper (SWT) method. FEA of the Aluminum 6061-T6 bracket revealed von Mises stress levels ranging between 170–204 MPa, which approach the material's yield strength of 208 MPa. The Soderberg result (1.717 > 1) did not meet the safe design criterion, which was further validated by the occurrence of fracture during field application. The fatigue life predicted by the SWT method was 9.81 × 10^9 cycles. The alternative bracket design made from ST52 steel yielded more favorable results with lower stress levels (100–115 MPa). For this design, the Soderberg value was found to be 0.485 (< 1), indicating a structurally safe configuration. Additionally, a fatigue life of 3.87 × 10^11 cycles was obtained using the SWT method, and approximately 10^6 cycles according to FEA-consistent with the infinite life threshold reported in the literature. The findings highlight the critical influence of material selection and structural geometry on fatigue performance. The ST52 steel bracket demonstrated superior performance in terms of both safety and durability, providing a methodological basis for fatigue-resistant design in electric bus components.

Keywords: Fatigue Life, Finite Element Analysis (FEA), Smith-Watson-Topper Method, Soderberg Approach

Özet

Bu çalışma, M3 sınıfı bir elektrikli otobüsün şarj kapağı mekanizmasında kullanılan iki farklı braket tasarımının biri Alüminyum 6061-T6, diğeri ST52 yapısal çeliğinden üretilmiş yorulma dayanımı açısından kapsamlı bir değerlendirmesini sunmaktadır. Her iki braket, gerçek servis verilerinden elde edilen sabit genlikli çevrimsel yüklere maruz bırakılmıştır. Yorulma ömrü tahminleri, sonlu elemanlar analizi (FEA) ve iki farklı yöntem olan gerilme temelli Soderberg kriteri ile gerilme temelli Smith-Watson-Topper (SWT) yöntemi kullanılarak gerçekleştirilmiştir. Alüminyum 6061-T6 braketi için yapılan FEA, 170–204 MPa aralığında von Mises gerilmeleri ortaya koymuş; bu değerler malzemenin 208 MPa'lık akma sınırına oldukça yakındır. Soderberg sonucu (1.717 > 1) güvenli tasarım kriterini karşılamamış ve bu durum saha uygulamasında meydana gelen kırılmayla da doğrulanmıştır. SWT yöntemiyle elde edilen yorulma ömrü ise 9,81 × 10^9 çevrim olarak hesaplanmıştır. ST52 çeliğinden imal edilen alternatif braket tasarımı ise daha düşük gerilme seviyeleri (100–115 MPa) ile daha avantajlı sonuçlar vermiştir. Bu tasarım için Soderberg değeri 0.485 <1 olarak bulunmuş ve güvenli bir yapı olduğunu göstermiştir. Ayrıca SWT yöntemiyle 3,87 × 10^11 çevrimlik yorulma ömrü elde edilmiş, FEA analizine göre ise yaklaşık 10^6 çevrim sonucuna ulaşılmış ve literatürdeki sonsuz ömür eşiğiyle uyum sağlanmıştır. Elde edilen sonuçlar, malzeme seçimi ve yapısal geometrinin yorulma performansı üzerindeki kritik etkisini ortaya koymaktadır. ST52 çeliğinden üretilen braket hem güvenlik hem de dayanıklılık açısından üstün performans sergilemiş ve elektrikli otobüs bileşenlerinde yorulma dayanımına yönelik tasarım sürecine katkı sağlayacak metodolojik bir temel sunmuştur.

Anahtar kelimeler: Yorulma Ömrü, Sonlu Elemanlar Analizi (FEA), Smith-Watson-Topper Yöntemi, Soderberg Yaklaşımı

1 Introduction

Recent advancements in the fields of engineering and materials science have led to significant progress in the investigation of fatigue strength and its adoption as a design criterion. This process plays a crucial role in increasing the safety factors of components used across various industries. By improving material properties and design criteria, fatigue strength can be enhanced, allowing components to be used in a more durable and safe manner. Current studies have made fatigue strength a fundamental key for achieving efficient and safe structures in engineering applications.

Fatigue is the process by which a material weakens and undergoes damage due to repeated loads over time and as a function of the number of cycles, without reaching the yield limit. This phenomenon is a commonly encountered term both in literature and in everyday life. In modern engineering applications, it emerges as one of the key factors determining the reliability and lifespan of components. Fatigue can lead to unexpected damage of structures or components.

The periodic application of tensile and compressive loads to parts generates negative and positive sinusoidal waves on the material, accelerating the fatigue process.

Eryılmaz et al. developed a methodology for the design of engine brackets exposed to dynamic effects by comparing the test results of an 18-meter Euro VI commercial vehicle. The vehicle and road model prepared in the computer environment validated the research conducted with previously obtained road data [1].

Dong et al. examined the fatigue performance of a wire bracket for rail vehicles with different vibration amplitudes and compared the fatigue life of the wire bracket through computer-assisted simulations [2].

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Liu et al. attached accelerometer sensors to a bracket located on the underside of rail vehicles in metro systems, which supports the wheel sets. They converted the acceleration values obtained during operation into a frequency-based format and compared them with the natural frequency of the bracket. The results revealed that the bracket resonated around 61 Hz, and stress concentrations increased around the hole area of the bolt [3]. While these examples illustrate the importance of fatigue analysis in transportation-related brackets, the present study extends the scope to electric buses and focuses on constant amplitude loading derived from service conditions, integrating fatigue life models for enhanced structural evaluation.

In the process of fatigue life prediction, this study highlights the significant impact of out-of-plane bending (OPB) on the fatigue performance of chain link structures. Barros et al. (2023) developed both analytical equations and a finite element model to evaluate the fatigue life of metallic chain links used in mooring systems, considering axial stress and OPB effects. Their work demonstrated that the presence of OPB significantly increases normal stress at the hotspot, which in turn drastically reduces fatigue life, particularly under constant amplitude loading conditions. Fatigue life was calculated using the Smith-Watson-Topper (SWT) criterion and validated through ABAQUS simulations. In the present study, a similar methodological approach is adopted to evaluate the fatigue behavior of a critical structural component the charging door bracket subjected to constant cyclic loads. By integrating experimentally validated fatigue parameters, the use of SWT criteria, and service-representative loading conditions, this research bridges the gap between generic fatigue models and their application in real-world electric bus components [4].

Fatigue life prediction remains a fundamental requirement for the safe operation of components exposed to cyclic loads, especially in the automotive industry. Chin et al. (2021) investigated the fatigue performance of coil springs under variable amplitude loading using conventional strain-based models. Among the models evaluated, the Smith-Watson-Topper (SWT) criterion was found to yield more accurate fatigue life predictions than Coffin-Manson and Morrow models, particularly when high-amplitude cycles were present. Although btheir study focused on suspension components and random loading, the demonstrated effectiveness of the SWT approach provides strong support for its application in structural fatigue assessment under well-defined cyclic conditions, such as those analyzed in the present study [5].

In the design phase of structures subjected to dynamic loading, regions with sharp geometric features may serve as initiation points for fatigue cracks due to notch effects. Nominal stresses can be used to reliably predict the fatigue strength of notched components. This method can be combined with fatigue strength factors to reduce the effects of notches [6].

In structural connections, the stress concentration in notched areas can be the initiation point for fatigue cracks, thus these regions should be carefully considered in the design [7].

In automotive applications, brackets, particularly welded connection areas, are weak points prone to fatigue damage. Welding defects in these connections can adversely affect fatigue life under high-frequency vibrations. Xue and his team noted that vibrations, especially in welded areas, cause fatigue failures, and these findings are crucial for bracket designs in the automotive sector [8].

The Finite Element Analysis (FEA) method is an effective tool for predicting stress concentrations and analyzing the initiation of fatigue cracks to optimize the fatigue life of structural components [9].

Studies on the accumulation of fatigue damage in critical regions of brackets have shown that porous structures and low-density areas within materials significantly influence this process. In analyses conducted by Brusa and colleagues, fatigue cracks were observed to initiate and propagate in the critical load-bearing areas of titanium alloy brackets produced via additive manufacturing. These findings provide a valuable analogue for understanding similar damage accumulation phenomena in metal brackets used in transportation systems, including electric buses [10].

The accumulation of fatigue damage and its impact on material life is a significant research topic in the field of engineering. Liu and Ma (2023) conducted a review of various theoretical models used to explain the fatigue damage of metallic materials. The study compares linear and nonlinear cumulative damage models with data analyses, emphasizing that the nonlinear damage model is more suitable for constant and multi-stage variable amplitude loading. Among the models reviewed, nonlinear cumulative damage models especially those incorporating energy dissipation and strength degradation were found to yield more accurate fatigue life predictions, particularly under constant and multi-level amplitude loading conditions [11].

The fatigue life of brackets is considered a critical parameter for safety and durability in engineering structures. In a study conducted by Yang, Liu, and Wang (2023), the effect of environmental temperature on the fatigue life of carbon fiber reinforced polymer (CFRP) materials was investigated. A temperature-based property curve and a performance fraction model for the shaft were developed, and fatigue life predictions were made using experimentally obtained temperature coefficients. Additionally, factors such as load mean, amplitude, and environmental temperature were evaluated for their influence on fatigue performance. Although this study focused on composite materials under random loading conditions, it underscores the increasing relevance of fatigue-oriented design approaches. This methodology, while developed for composites, lays a foundation for incorporating environment-related factors into fatigue models an approach increasingly important for metallic systems under service conditions, such as bus brackets. This study contributes to a more accurate analysis of the fatigue behavior of CFRP materials [12].

The initiation point of fatigue cracks in non-welded steel components constitutes a significant portion of the total fatigue life, and accurately predicting this phase is crucial for structural integrity. Hao et al. (2023) developed a numerical model that integrates the extended finite element method (XFEM) with the Smith–Watson–Topper (SWT) damage model to estimate the fatigue crack initiation life in notched steel components. Their approach, validated by experimental tests, demonstrated that the SWT-based cycle-by-cycle damage accumulation method can reliably predict fatigue life under high-cycle loading. In parallel with this methodology, the present study applies SWT theory to assess the fatigue performance of a bracket located on the charging door of an electric bus. This component, although not notched in the same geometrical sense, features stress-concentration-prone zones that behave similarly under cyclic loading, reinforcing the relevance of SWT-based modeling for life estimation in structural brackets under service-like conditions [13].

Recent studies have explored fatigue behavior in structural components using both experimental and numerical methods. For instance, Usta et al. (2016) conducted fatigue testing on ST52 steel using rotating bending tests, while the fatigue performance of aluminum alloys such as 6061-T6 has been standardized in MIL-HDBK-5H (1998). More recent work by Braun et al. (2024) and Zhao et al. (2025) highlighted that geometric discontinuities such as notches and fillets are dominant sites for fatigue crack initiation under cyclic loading [14], [15], [16], [17]. Although these studies provide valuable insights into material fatigue properties, they often focus on generic specimens and simplified boundary conditions. In contrast, the present study evaluates the fatigue performance of a functionally critical component the charging door bracket of an M3-class electric bus [1 under realistic loading conditions derived from service measurements. By integrating mesh-converged finite element analysis with both Soderberg and SWT fatigue models, and by comparing two alternative designs across two different materials, this study fills a methodological gap in the literature and offers practical guidance for improving the structural durability of public electric transportation systems.

The classical Soderberg criterion remains one of the most widely adopted methodologies in fatigue design, especially for high-cycle loading scenarios where preliminary assessments are critical. Despite the emergence of more advanced multiaxial fatigue models in recent years, the simplicity and conservative nature of the Soderberg approach ensure its continued relevance in the design of mechanical components subjected to cyclic loading. According to de Castro (2024), the Soderberg formulation offers a practical foundation for quick safety evaluations, particularly in engineering education and early-stage design of machine elements. Moreover, this study emphasizes that while various interpretations of the classical approach exist in the literature, Soderberg's line-based criterion remains instrumental in defining safety margins for components under combined stress states. In the present study, the Soderberg criterion is applied to assess the fatigue safety of charging door brackets under constant amplitude loading, offering a conservative benchmark for comparison against strain-based models like SWT [18].

In the context of high-cycle fatigue design, the Soderberg criterion continues to serve as a conservative benchmark for evaluating safety margins, particularly under combined loading conditions. Henriques et al. (2021) conducted a systematic comparison between the Soderberg approach and the DIN 743 fatigue standard. Their results showed that the Soderberg method consistently yielded lower safety factors across various stress combinations, confirming its conservative nature. These findings support the relevance of the Soderberg criterion in preliminary fatigue assessments of structural components, especially in public transportation systems where reliability is paramount. In this study, the Soderberg approach is adopted as a baseline to assess the fatigue safety of two bracket designs under constant amplitude cyclic loading [19].

Fatigue life is a concept of critical importance in engineering applications. Brackets, which operate under constant amplitude loads, are subjected to repeated stress cycles over time. This condition increases the risk of material fatigue and, consequently, structural damage. Constant amplitude fatigue life helps predict the number of cycles a material can endure before fatigue cracks form when exposed to a specific stress level. This study aims to explore existing theories and experimental findings regarding constant amplitude fatigue life, examining their effects on bracket design and durability analysis. Considering different material types and design approaches, the development of innovative strategies to extend fatigue life becomes crucial. To ensure that brackets can be used safely and efficiently, conducting such analyses and optimizations will enhance the success of engineering applications.

Although fatigue life comparison of different materials is a well-explored area, this study focuses on a rarely addressed structural detail: the bracket supporting the charging door of an M3-class electric bus. This component is subjected to cyclic forces during each charging operation, making it critical in terms of fatigue performance. Unlike generic material tests, this study integrates real-world load data, realistic boundary conditions, and mesh-converged finite element analysis to evaluate both stress concentration zones and life prediction models (Soderberg and SWT). As such, the study contributes not only material-specific results, but also a methodological framework for application-oriented fatigue design in electric vehicle infrastructure.

2 Materials and methods

This study is a numerical analysis conducted to evaluate the fatigue life of a bracket located in the charging cover area of a bus under constant amplitude loads, using Finite Element Analysis (FEA) and fatigue life prediction models. To analyze the performance differences between the old and new bracket designs, both models have been thoroughly examined and compared.

2.1 Technical specifications of the bracket

Two different bracket models were studied, and based on the loading and fatigue behavior experienced by the old bracket throughout its service life, a new bracket design was developed, completely changing both the material and the design. In this study, the first bracket was made from Al 6061-T6, while for the second bracket, in addition to the design changes, the material was altered to St52 quality steel, which is commonly referred to as structural steel in the literature and is expected to have a higher fatigue life. The mechanical properties of both materials are provided in Table 1.

Table 1. Mechanical properties of the materials used for the bracket [14], [15].

Mechanical Properties	Al 6061-T6 Series	St52 Steel
Yield Strength	208 MPa	355 MPa
Tensile Strength	310 MPa	559 MPa
Poisson's Ratio	0,33	0.3
Elastic Modulus	68900 MPa	207000 MPa

In addition to the mechanical properties of the materials, fatigue life predictions in this study are based on S-N curves, which play a critical role in evaluating the bracket's behavior under cyclic loading. The S-N curve used for the aluminum 6061-T6 material (Figure 1) was derived from the MIL-HDBK-5H handbook (1998), which compiles statistically processed experimental fatigue test data conducted under various stress ratios for aerospace-grade materials [14]. For the ST52 steel material (Figure 2), the S-N curve was obtained from the experimental study by Usta et al. (2016), where rotating bending fatigue tests were conducted in accordance with ASTM E466 and E468 standards. These tests involved seven stress levels and three repetitions per level, yielding a comprehensive fatigue performance profile [15]. Thus, the S-N curves used in this study are grounded in experimentally validated literature sources and conform to internationally recognized standards, ensuring their reliability for fatigue life estimation.

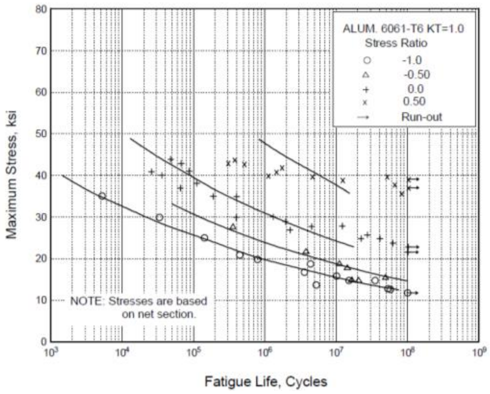


Figure 1. S-N curve for al 6061 t6 [14].

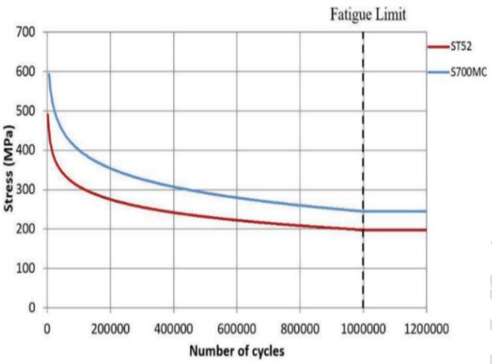


Figure 2. S-N curve for st52 quality steel materials [15].

2.2 Bracket design

Two different designs for the bracket were considered in this study (Figure 3). In the first design, the old bracket made of Al 6061 T6 material, which deforms over time depending on the bus's charging cap closing mechanism, was used. This bracket fails to provide sufficient strength in the current design and undergoes deformation due to material fatigue. To improve this situation, in the second design, St52 quality structural steel, which offers higher strength and fatigue resistance in terms of material properties, was chosen. As a result, the structural durability of the new bracket design was enhanced, aiming for a longer service life.

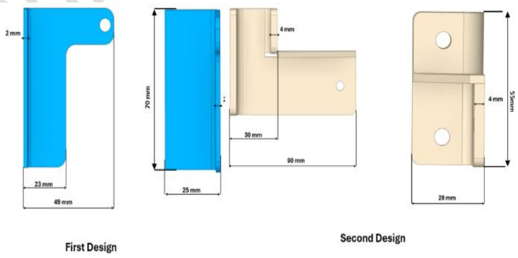


Figure 3. Bracket designs.

2.3 Finite element model and boundary condition

The finite element mesh was developed using ANSYS Mechanical, based on 3D geometry created in CATIA V6. For the first bracket design, the mesh consisted of 466,559 nodes and 101,728 elements. High-order hexahedral SOLID186 elements were employed due to their superior ability to capture stress gradients in fatigue-critical areas compared to lower-order or tetrahedral elements [20].

As presented in Figure 4, the generated mesh exhibited an average element quality of 0.96, a maximum skewness of 0.72, and an average orthogonal quality of 0.98. These values fall within acceptable limits for structural fatigue simulations, as reported in the literature [21].

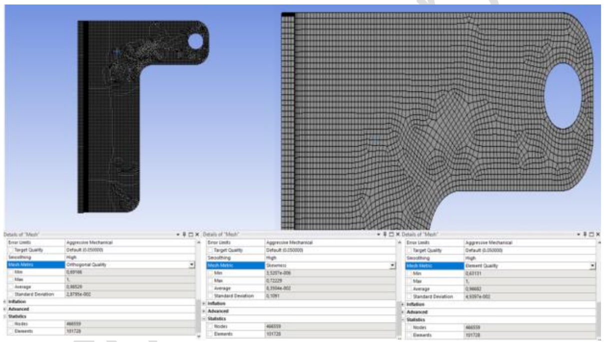
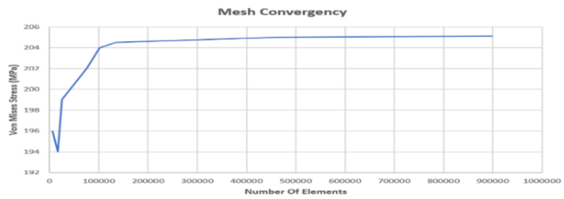


Figure 4. Finite element mesh created for the first bracket,

To validate the mesh independence, a convergence study was carried out. Element sizes of 4 mm, 3 mm, 2 mm, and 1 mm were tested, and the maximum von Mises stress values were monitored at a critical location near the loading point. As shown in Figure 5, the stress difference between the 2 mm and 1 mm meshes was less than 0,5%, confirming that the mesh was sufficiently refined. This convergence behavior supports the numerical reliability of the simulation results and is essential for accurate fatigue assessment [22]. Therefore, the 2 mm mesh was selected for subsequent simulations to maintain a balance between computational efficiency and solution accuracy.



Elemen size (mm)	Number of Elements	Max. Von Mises Stress (MPa)	Stress Difference (%)	Converged
5	15000	193.5	0	No
4	40000	200.4	3.57	No
3	80000	200.3	1.95	No
2	101728	205.83	0.75	Yes
1.5	250000	205.95	0.06	Yes
1	500000	206.05	0.05	Yes
0.75	750000	206.1	0.02	Yes
0.5	900000	206.12	0.01	Yes

Figure 5. First Bracket Mesh independence graph.

The finite element mesh for the second bracket was constructed using the same methodology and meshing criteria applied to the first design. As shown in Figure 6, the model consisted of 239,424 nodes and 106,275 elements. Hexahedral SOLID186 elements were again used to ensure high solution accuracy in regions of stress concentration [20].

The generated mesh exhibited an average element quality of 0.93, a maximum skewness of 0.76, and an average orthogonal quality of 0.98. These values fall within the acceptable limits for structural fatigue analyses and indicate that the mesh was of sufficient quality to provide reliable numerical results [21].

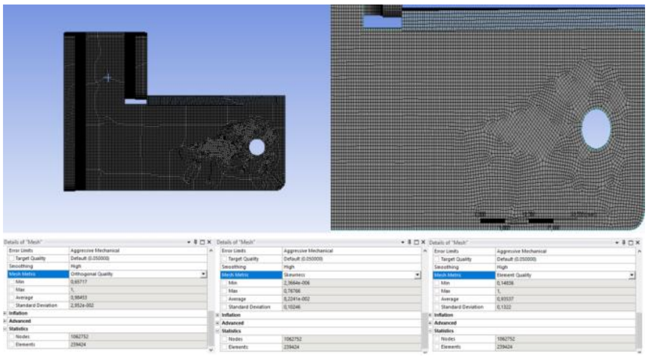
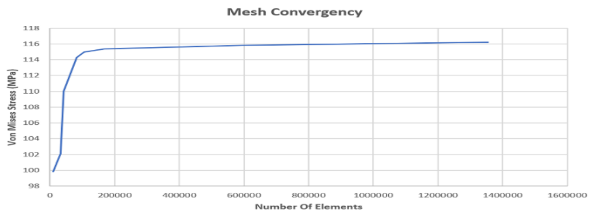


Figure 6. Finite element mesh created for the second bracket.

To confirm mesh independence, a convergence study was also performed for this design. The element size was gradually refined, and the maximum von Mises stress values were monitored at a critical location. As illustrated in Figure 7, the stress values converged beyond approximately 200,000 elements. The difference between the final two mesh densities was less than 0.5%, confirming that convergence was achieved [22]. Therefore, the selected mesh configuration was deemed appropriate for all subsequent fatigue life simulations.



Elemen size (mm)	Number of Elements	Max. Von Mises Stress (MPa)	Stress Difference (%)	Converged
5	15000	99.2	0	No
4	40000	109.6	10.48	No
3	100000	114.8	4.74	No
2	200000	115.4	0.52	Yes
1.5	400000	115.6	0.17	Yes
1	800000	115.8	0.17	Yes
0.75	1200000	116	0.17	Yes
0.5	1400000	116	0	Yes

Figure 7. Second Bracket Mesh independence graph.

To accurately simulate the operational conditions of the bus charging lid brackets, a constant amplitude cyclic load was applied to both bracket designs. This load replicates the repetitive opening and closing actions experienced during regular operation. The load magnitude was set to vary between +75 N and 0 N, based on empirical measurements obtained from the actuator mechanism responsible for lid movement. Such loading conditions represent high-cycle fatigue, where components are subjected to numerous cycles of low-to-moderate stress amplitudes [23].

The load was applied at the hole located on the upper arm of each bracket, corresponding to the connection point with the mechanical actuator. The direction of the applied force was set along the negative Y-axis, replicating the real force vector direction measured during operation. To realistically reflect the physical mounting conditions, the brackets were fixed at their base surfaces, simulating the rigid attachment to the vehicle's chassis. All six degrees of freedom translations and rotations in the X, Y, and Z directions were fully constrained at these mounting points. Accurate definition of boundary conditions is essential for obtaining reliable fatigue predictions, as constraints directly influence the stress distribution throughout the part [24].

The boundary conditions and loading definitions follow best practices widely used in finite element-based fatigue simulations. Proper application of constraints and loading scenarios is critical for the validity of numerical fatigue life estimation [25]. Figure 8 illustrates the applied boundary conditions, the fixed regions, and the loading direction for both bracket designs.

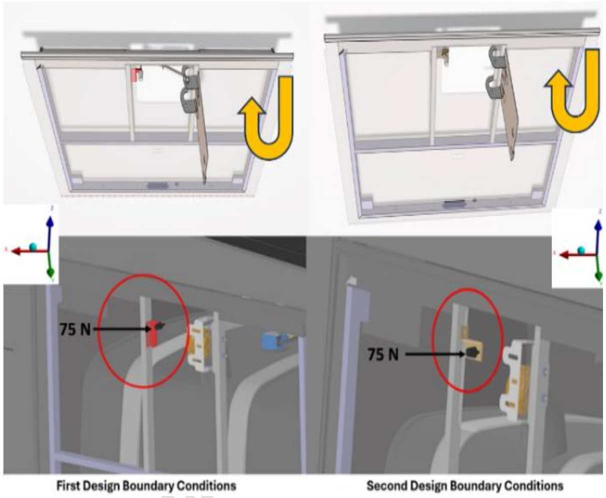


Figure 8. Boundary conditions of the brackets on the bus.

The applied loading was modeled as a constant amplitude cyclic force ranging from 0 N to 75 N, representing the operational stresses encountered during repeated lid actuation. The idealized force profile for each open-close cycle is illustrated in Figure 9.

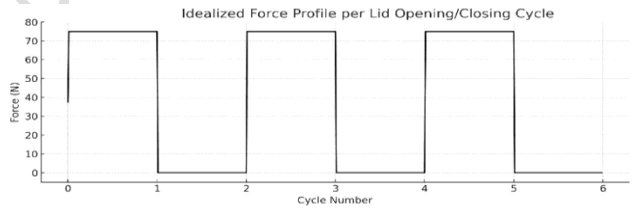


Figure 9. Cyclic force pattern per lid actuation cycle.

2.4 Fatigue life prediction methods

In the prediction of fatigue life, the Smith-Watson-Topper (SWT) model and the Soderberg method in combination with the finite element method (FEM) have been employed. These theories are commonly applied to estimate the fatigue strength of materials, particularly under cyclic loading conditions. The Smith-Watson-Topper (SWT) method predicts fatigue life based on a single cyclic stress amplitude and mean stress value of the material, and it is particularly useful under complex loading scenarios such as torsion and bending. In this study, a stress ratio (R) of -1 has been assumed for both the Soderberg and SWT approaches, and Equation (4) has been utilized accordingly in the fatigue life calculations.

2.4.1 SWT Fatigue Parameter

The Stress-Life Approach is based on the principles of high cycle fatigue (HCF) and low cycle fatigue (LCF). In high cycle fatigue, the cyclic stress amplitudes, Δ_{ϵ} , are within the material's elastic range. In low cycle fatigue, the cyclic plastic strain amplitudes, $\Delta_{\epsilon p}$ are considered.

For high cycle fatigue, the Basquin equation and for low cycle fatigue, the Coffin-Manson equation are used. These are as follows:

$$\left(\frac{\Delta_{\epsilon_{\epsilon}}}{2}\right) = \frac{\dot{\sigma_f}}{E}(2N_f)^b \quad (1)$$

$$\left(\frac{\Delta_{\epsilon_p}}{2}\right) = \dot{\epsilon}_f \ (2N_f)^c \quad (2)$$

In this context $\dot{\sigma_f}$ and b represent the fatigue strength coefficient and exponent, respectively, while $\dot{\epsilon}_f$ and c represent the fatigue ductility coefficient and exponent. $2N_f$ refers to the number of

cycles until failure, and E represents the modulus of elasticity.

The total strain can be related to the fatigue life through the following stress-life equation. This equation is the sum of the Basquin equation and the Coffin-Manson equation:

$$(\frac{\Delta_{\epsilon}}{2})_{Total} = \frac{\dot{\sigma_f}}{E}(2N_f)^b + \dot{\epsilon}_f \ (2N_f)^c \quad (3)$$

It is known that this equation does not take into account the effects of mean stress and nominal stress on the fatigue life. While it considers the effects of stress amplitude and plastic deformation, it does not account for the combined effects of mean stress and stress amplitude.

Therefore, a more comprehensive approach is required for fatigue life predictions. The Smith-Watson-Topper (SWT) method aims to model the fatigue life more accurately by combining the effects of mean stress and stress amplitude. Based on this, the general form of the SWT method is given in Equation (4) [26]. In addition to its classical strain-based implementation, the SWT approach can also be utilized in a stress-based form, depending on the nature of the analysis and available data. Recent literature confirms the validity and applicability of stress-based SWT formulations. For instance, the review study by Łagoda et al. comprehensively discusses both classical and modified forms of the SWT parameter, including stress-based implementations, and provides updated insights into its use across various metallic materials [27].

$$SWT = \sigma_{max}\sqrt{\frac{1-R}{2}} \quad (4)$$

Here, σ_{max} represents the maximum stress, and R denotes the stress amplitude values. Using the obtained SWT parameter, the empirical formula for predicting the fatigue life is derived as follows:

$$N_f = \frac{C}{(SWT)^m} \quad (5)$$

In this case, N_f represents the number of cycles the material undergoes until failure, while C and m are the experimental constants determined for the material [28]. The value of the experimental constant C is generally accepted as 10^12 for steel materials and 8.48966^{12} for aluminum materials in the literature. The value of m is considered to be 0.5 for aluminum and 0.2 for steel, assuming that the bracket does not undergo high plastic deformation over time [13]. Since standard steel and aluminum materials are used in this study, the value of m has been taken as 1.

A review of the literature reveals that studies have been conducted in which the SWT approach is thoroughly examined, and the connection between sources is interpreted based on low and high cycle counts according to the SWT approach. These studies contribute to a more comprehensive understanding of fatigue analysis and facilitate more accurate predictions in applied engineering fields [29].

2.5 Soderberg approach

In the field of fatigue analysis, the Soderberg criterion is widely adopted as a conservative method to evaluate the structural durability of mechanical components under cyclic loading. This approach was developed to prevent failure by ensuring that the combined effects of mean and alternating stresses do not exceed the material's yield strength and ultimate tensile strength. Fatigue is defined as the progressive and localized structural damage that occurs when a material is subjected to cyclic loading, with the stress ratio and the magnitude of the mean stress significantly influencing the fatigue life. The Soderberg criterion incorporates these variables into a linear relationship, providing a safe design boundary, particularly for ductile materials. In the present study, the Soderberg approach is applied to the fatigue assessment of bracket components subjected to cyclic loading with a stress ratio (R) of -1, representing fully reversed tension-compression loading conditions. This methodology allows for the estimation of fatigue safety margins in critical structural components operating under symmetric tension-compression cycles (Figure 10).

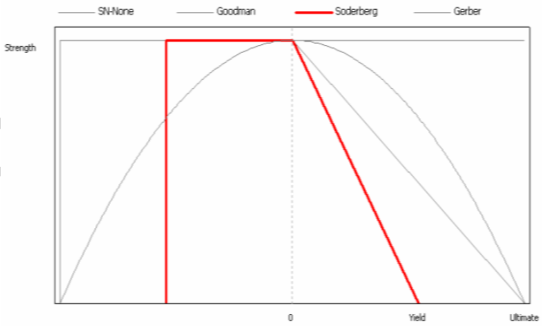


Figure 10. Soderberg curve [30].

The formulation of the Soderberg equation is as follows:

$$\frac{\sigma_{Alternating}}{\sigma_{Endurance\ Limit}} + \frac{\sigma_{mean}}{\sigma_{yield\ Strength}} \leq 1 \quad (6)$$

In the equation, $\sigma_{Alternating}$, represents the alternating stress value, $\sigma_{Endurance\ Limit}$, represents the fatigue strength, σ_{mean}, represents the mean stress value, and $\sigma_{yield\ Strength}$ represents the yield strength. As shown in Figure 9, the Soderberg approach focuses on providing a more secure result, as it takes into account the yield strength in addition to the Goodman and Gerber criteria. A result greater than 1 indicates that the component will not be able to operate safely during its working cycle, while all results below 1 indicate that it will operate in a safe region. According to the formulation used in this study, the fatigue strength of aluminum is considered to be 40% of the yield strength, and for steel, it is considered to be 50% of the yield strength. Calculations will proceed accordingly. Upon reviewing the literature, it is observed that the Soderberg approach is one of the important criteria for the safe prediction of fatigue life and has been actively studied in fatigue life predictions [31],[32].

3 Results

In this study, the fatigue life of existing and improved charge cover bracket designs has been evaluated using the Smith-Watson-Topper (SWT) method and finite element analysis

(FEA). Additionally, the fatigue strength has been predicted using the Soderberg method. The findings provide a detailed insight into the performance of bracket designs under different loading conditions and the effects of material properties. This section will present and interpret the stress distributions and the predicted fatigue lives obtained from the analyses conducted.

3.1 Finite element analysis results

When analyzing the finite element results for the first bracket design, significant stress levels were observed particularly around the load application region and at the fillet transition between intersecting surfaces. As shown in Figure 11, localized stress values ranged from approximately 170 MPa to 204 MPa, which are notably close to the yield strength of the aluminum 6061-T6 material. While the overall structure appears to retain its global integrity, these stress concentrations indicate potential hotspots for fatigue crack initiation. This is consistent with recent findings in fatigue research, where microcracks are observed to nucleate in regions of geometric discontinuity such as fillets and bolt holes due to amplified local stresses (Braun et al., 2024; Zhao et al., 2023; Zhang et al., 2023). Experimental studies have further shown that notch severity directly reduces the crack initiation life and accelerates early-stage fatigue damage. Therefore, such local stress evaluations are not only critical for realistic fatigue life predictions but also provide a methodological basis for improving bracket durability through geometry optimization [16], [17], [33].

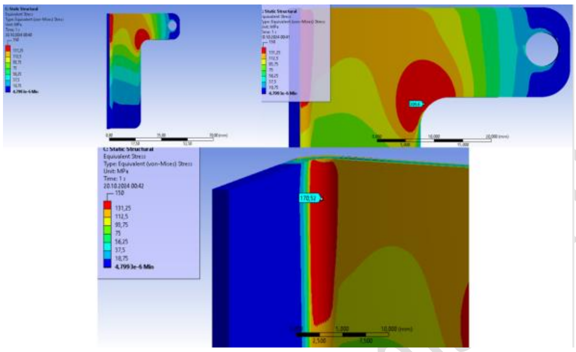


Figure 11. Stress distribution on the first bracket.

The first designed bracket was validated using the actual output of the bus charging lid, which showed that it failed to maintain structural integrity during cyclic loading over time. This resulted in the bracket breaking and causing damage to the charging lid (Figure 12).

Figure 12. Damage image of the bracket from the first design during application.

Based on the application results, a second alternative bracket design was developed using standard structural steel (ST52), which exhibits improved resistance to cyclic stresses. Finite element analyses were repeated for the revised geometry and material. Upon examining the results, it was found that the updated design achieved a more favorable and uniform stress distribution overall. As illustrated in Figure 13, localized stress values still appeared near the fillet and load application regions, ranging between 100 MPa and 115 MPa. However, these values remain well below the yield strength of the material, and the stress concentration is notably less severe compared to the first design. Consequently, the likelihood of fatigue crack initiation is significantly reduced, suggesting that the second bracket design offers superior durability under cyclic loading conditions.

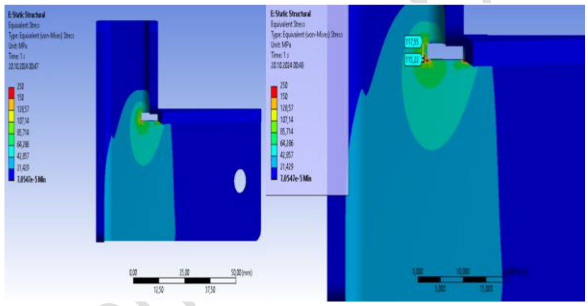


Figure 13. Stress distribution on the second design bracket.

According to the finite element results, when the fatigue life is calculated using the Soderberg approach, it was determined that the bracket from the first design would experience damage after 246.660 cycles of a 75 N cyclic load, as shown in Figure 14.

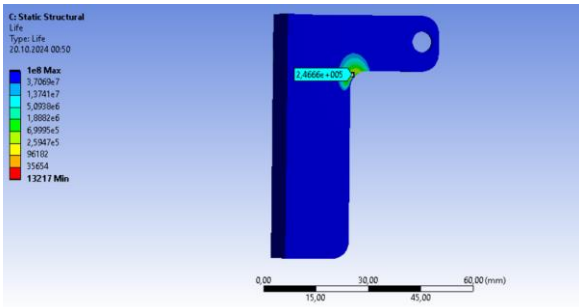


Figure 14. Estimation of life according to the soderberg approach for the first bracket.

According to the Soderberg approach presented in Equation 6, the alternating stress was calculated as half the difference between the maximum (204 MPa) and minimum (0 MPa) stress values, resulting in 102 MPa. The endurance limit was determined to be 83.2 MPa, based on literature findings which suggest that for aluminum materials, the fatigue strength can be taken as 40% of the yield strength [31], [32]. The mean stress was calculated as the average of the maximum and minimum stress values, and similarly found to be 102 MPa. The yield strength was assumed to be 208 MPa [14]. Based on these parameters, the Soderberg-based calculations are presented in Equations 7 and 8.

$$\frac{102\ \text{MPa}}{83.2\ \text{MPa}} + \frac{102\ \text{MPa}}{208\ \text{MPa}} \leq 1 \tag{7}$$

$$1.717 \leq 1 \tag{8}$$

This result indicates that the Soderberg criterion is not satisfied. In this case, it can be concluded that the bracket will not operate safely under cyclic loading conditions. The applications conducted on the bus corroborate these findings. When the Soderberg approach was applied to the second design, it was found that the regions experiencing maximum stress reached a cycle count of 1,000,000, which is generally accepted as the threshold for infinite life in fatigue design (Figure 15). For instance, Shigley and Mischke (2004) stated that most metallic materials are considered to have reached infinite life when subjected to more than 10^6 load cycles [34]. Similarly, according to the SAE J1099 fatigue design guidelines, 1 million cycles is often regarded as the endurance limit under constant amplitude loading [35]. In addition, Suresh (1998) emphasized that aluminum and steel alloys typically exhibit fatigue limits near the 10^6–10^7 cycle range under controlled conditions [36].

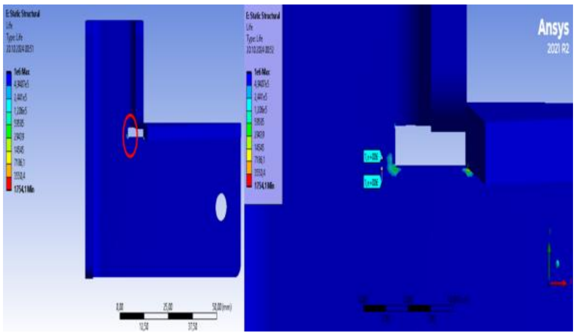


Figure 15. Estimation of life according to the soderberg approach for the second bracket.

Using the same method described in Equation 6, the alternating stress was obtained by taking half of the difference between the maximum stress (115 MPa) and the minimum stress (0 MPa), yielding a value of 57.5 MPa. The endurance limit was estimated based on literature, which commonly suggests that the fatigue strength of aluminum alloys can be approximated as 50% of their yield strength [31], [32]. Accordingly, the mean stress defined as the average of the maximum and minimum stress values was also calculated as 57.5 MPa. For the purposes of the analysis, the yield strength was taken as 350 MPa [15]. These values formed the basis for the Soderberg analysis, as outlined in Equations 9 and 10.

$$\frac{57.5\text{MPa}}{177.5\text{MPa}} + \frac{57.5\text{MPa}}{355\text{MPa}} \leq 1 \tag{9}$$

$$0.485 \leq 1 \tag{10}$$

Thus, it has been concluded that the design and material selection of the second bracket can safely operate under the specified loading conditions.

3.2 Fatigue life predictions using Smith-Watson-Topper (SWT) and S-N curve

In the scope of this study, the SWT approach is employed to determine the fatigue life:

For the first bracket made of aluminum material, the SWT stress is determined using Equation 4, and the cycle count is determined using Equation 5. The required maximum stress in Equation 4 is obtained as 204 MPa through finite element analysis, and based on this, the corresponding calculations are provided in Equations 11 and 12.

$$SWT = 204\ MPa \tag{11}$$

$$N_f = \frac{8.48966^{12}}{(204)^{0.5}} = 9.81x10^9 \tag{12}$$

When similar calculations were made for the new design manufactured from steel, the SWT stress was determined using Equation 4, and the cycle count was determined using Equation 5. The required maximum stress in Equation 4 was obtained as 115 MPa through finite element analysis, and based on this, the calculations are provided in Equations 13 and 14.

$$SWT = 115\ MPa \tag{13}$$

$$N_f = \frac{10^{12}}{(115)^{0.2}} = 3.87x10^{11} \tag{14}$$

Based on the obtained results, it is observed that the St52 quality steel material provides a longer operational lifespan according to the SWT approach. For the lifespan prediction of the brackets, the S-N curve of the relevant aluminum material, as shown in Figure 1, needs to be utilized (Table 2). When making lifespan predictions from the S-N curve, an interpolation method will be applied to reach the result. In this context, the set of equations to be used is as follows:

$$N = N_1 + \frac{(\sigma - \sigma_1) - (N_2 - N_1)}{(\sigma_2 - \sigma_1)} \tag{15}$$

Table 2. S-N curve of al 6061 – t6 material.

Cycles (N)	Stress (MPa)
100.000.000	82.74
55.000.000	89.63
2.400.000	117.2
800.000	137.9
140.000	172.4
34.000	206.8
5.000	241.3
1.700	275.8

Based on the calculations using Table 2, values of σ_1=206.8 MPa and N_1=34000 as well as σ_2=172.4MPa and N_2=140000, were determined, with the maximum stress σ=204 MPa taken as a reference based on the FEM analysis results obtained on the bracket. According to the interpolation calculations derived from these results:

$$N = 34000 + \frac{140000 - 34000}{172.4 - 206.8} x(204 - 206.8) \tag{16}$$

$$N = 34000 + \frac{10600}{-34.4} x(-2.8) \tag{17}$$

$$N = 34000 + (-3082.35)x(-2.8) \tag{18}$$

$$N = 34000 + 8619.65 = 42619 \tag{19}$$

According to the interpolation performed on the S-N curve, it has been determined that the bracket made of aluminum material and subjected to time-dependent damage will fail after 42.616 cycles. However, the interpolation performed here is valid for situations where the material operates in complete cycles.

Similarly, when the same calculations are made for the steel material used in the second design, the S-N curve for steel, provided in Figure 1, has been used as a reference in the same way (Table 3).

Table 3. S-N curve of st-52 material.

Cycles (N)	Stress (MPa)
1.200.000	200
110.000	205
50.600	230
11.000	300
1.524	400
1.000	420
673	440
450	460
250	480
150	490

Using the data obtained from Table 3, when the stress distribution on the second bracket was examined, it was concluded that the stress values ranging between 100-115 MPa on the bracket correspond to the infinite life region when referenced with the S/N curve for St52 structural steel provided in Figure 1.

In the literature, it has been observed that the S-N curve is one of the key parameters in calculating fatigue life. In this regard, successful studies have been conducted by utilizing the S-N curve to calculate the fatigue life for different materials [37].

4 Conclusions

This study presents a comprehensive fatigue evaluation of two bracket designs one made of Aluminum 6061-T6 and the other of ST52 structural steel used in the charging door mechanism of an M3-class electric bus. Constant amplitude cyclic loading, derived from real-world service conditions, was applied to both brackets. Fatigue life predictions were conducted using finite element analysis (FEA) in combination with two distinct methods: the stress-based Soderberg criterion and the stress-driven Smith-Watson-Topper (SWT) method.

These models were evaluated independently to maintain theoretical integrity. The Soderberg approach was employed to assess structural safety under combined static and alternating stresses, whereas the SWT method estimated high-cycle fatigue life based on localized stress response.

For the bracket manufactured from Aluminum 6061-T6, FEA results showed von Mises stress values ranging between 170 MPa and 204 MPa, approaching the material's yield strength of 208 MPa. The calculated Soderberg value of 1.717 (>1) indicated that the bracket did not meet the safety requirements. The SWT method, despite predicting a fatigue life of 9.81×10^9 cycles, could not override this safety limitation. FEA-based fatigue life was estimated at approximately 246,660 cycles. This concern was validated by field observations, where the aluminum bracket failed during regular operation.

In contrast, the ST52 steel bracket exhibited a significantly improved stress distribution, with von Mises stresses between 100 MPa and 115 MPa well below the material's 355 MPa yield strength. The Soderberg result of 0.485 (<1) confirmed that the bracket operated within safe design limits. The SWT method estimated a fatigue life of 3.87×10^{11} cycles, and FEA-based results exceeded 10^6 cycles, classifying the design within the "infinite life" domain according to standard literature.

These findings highlight that both material selection and structural geometry play a decisive role in fatigue performance. The ST52 bracket, due to its superior mechanical characteristics, fulfills the structural integrity requirements under cyclic loading more effectively than the Aluminum 6061-T6 design. The methodology merging validated FEA simulations with dual fatigue life prediction approaches establishes a robust framework for the fatigue assessment of structural components in electric vehicle systems.

In future research, emphasis may be placed on modeling variable amplitude loading scenarios and incorporating long-term service data for even more accurate fatigue life estimations. Additionally, experimental validation of high-stress concentration regions identified via FEA particularly around bolt holes and fillet transitions could improve confidence in simulation-based design practices.

5 Author contributions statement

In the conducted study, Author 1 contributed to the development of the idea and the literature review; Author 2 contributed to the analysis and evaluation of the designed components based on the literature review; and Author 3 contributed to the design process and the evaluation of the manuscript's content.

6 Ethics committee approval and conflict of interest statement

Ethics committee approval is not required for the prepared manuscript. There is no conflict of interest with any individual or institution in the prepared manuscript.

7 References

[1] Eryılmaz E, Pekbey Y, Küçük Ö. "Hızlandırılmış yorulma testleri ile motor braketlerinin analiz metodolojisinin geliştirilmesi". 8. Otomotiv Teknolojileri Kongresi, Bursa, Türkiye, 1-7 Mayıs 2016.

[2] Dong Z, Wang W, Dai S, Zheng J, Feng Y. "Study on structure optimization and vibration fatigue damage of wire bracket for rail vehicles". Engineering Failure Analysis, 156, 107732, 2024.

[3] Liu K, Wu X, Chi M, Wen Z. "Research on vibration fatigue of sensor bracket in a metro bogie based on the pseudo excitation method". Engineering Failure Analysis, 145, 107046, 2023.

[4] Barros L de O, Hansen FA, Neves RS, Ferreira GV, Morales LLD, Malcher L. "Fatigue life estimate of metallic chain links of mooring systems assuming out of plane bending: From constant amplitude to random loading". Ocean Engineering, 288, 116139, 2023.

[5] Chin CH, Rahim AAA, Abdullah S, Singh SSK, Md Nor N. "Acceptability of the effective strain damage model for fatigue life assessment considering the load sequence effect for automotive coil spring". Engineering Failure Analysis, 126, 105462, 2021.

[6] Susmel L. "Notches, nominal stresses, fatigue strength reduction factors and constant/variable amplitude multiaxial fatigue loading". International Journal of Fatigue, 162, 106941, 2022.

[7] Irving S, Ferguson-Smith F, Hu XZ, Liu Y. "Comparative fatigue assessment of soft toe and nested bracket welded aluminum structures". Engineering Failure Analysis, 12, 679-690, 2005.

[8] Wei X, Ren Z, Yang G. "Investigation into fatigue failure of cable brackets and vibration suppression methods". Engineering Failure Analysis, 165, 108782, 2024.
[9] Thillikkani S, Nataraj M, Luther King MF. "Failure analysis of shackle bracket in Airbus suspension under dynamic loading conditions". Engineering Failure Analysis, 120, 105087, 2021.
[10] Brusa E, Sesana R, Ossola E. "Numerical modeling and testing of mechanical behavior of AM titanium alloy bracket for aerospace applications". Procedia Structural Integrity, 5, 753-760, 2017.
[11] Liu X, Ma M. "Cumulative fatigue damage theories for metals: Review and prospects". Journal of Mechanical and Automotive Engineering, Shanghai University of Engineering Science, 1(1), 1-12, 2023.
[12] Yang X, Liu X, Wang J. "Random fatigue life analysis of carbon fiber-reinforced plastic for automotive drive shaft with environmental temperature data". Journal of Mechanical Engineering Science, 45(2), 123-135, 2023.
[13] Hao R, Wen Z, Xin H, Lin W. "Fatigue life prediction of notched details using SWT model and LEFM-based approach". Journal of Structural Engineering, 67(4), 455-468, 2023.
[14] U.S. Department of Defense. "MIL-HDBK-5H: Metallic materials and elements for aerospace vehicle structures". 1 December 1998.
[15] Usta T, Çiçek A, Uçak N, Çelik V, Ağca S. "Performance evaluation of S700MC and ST52 steels in terms of mechanical properties and fatigue life". Metal 2016, Brno, Czech Republic, EU, 549-554, 25-27 May 2016.
[16] Braun M, Chen T, Shen J, Dancette S, Requena G, Menou E, Vayre B, Doumalin P, Boller E. "Fatigue crack initiation and propagation in plain and notched PBF-LB/M, WAAM, and wrought 316L stainless steel specimens". Materials & Design, 244, 113122, 2024.
[17] Zhao Z, Hu X, Guo Z. "Effect of notches on fatigue crack initiation and early propagation behaviors of a Ni-based superalloy at elevated temperatures". Metals, 13(4), 384, 2023.
[18] Childs P R N. "Clarification on classical fatigue design for biaxial stress fields". Journal of Applied Mechanics and Materials, 8(6), 125, 2024.
[19] Henriques B, Carvalho M, Tavares S M O, de Castro P M S T. "A comparison of safety factor values for Soderberg and DIN 743 fatigue analyses". U. Porto Journal of Engineering, 7(2), 11–21, 2021.
[20] Zhang J, Li Y, Wang Y, Li H. "Fretting fatigue experiment and finite element analysis for dovetail structures". Applied Sciences, 11(21), 9913, 2021.
[21] Fatchurrohman N, Chia S T. "Performance of hybrid nano-micro reinforced Mg metal matrix composites brake calliper: simulation approach". IOP Conference Series: Materials Science and Engineering, 257, 012060, 2017.
[22] Chitransh C S, Saxena S. "Mesh convergence study for the assessment of fatigue life of the Al-MMC HPDC brake drum component". International Journal of All Research Education and Scientific Methods, 11(8), 2010–2013, 2023.
[23] Zhou M, Yin H, Zhang T, Zhang H, Liu G. "The Fatigue Life Analysis of the Battery Bracket". International Conference on Advances in Energy and Environmental Science, Atlantis Press, 2015.
[24] Johansson M. "Fatigue analysis of engine brackets subjected to road induced loads". DiVA Portal, 61(1), 1–56, 2016.
[25] COMSOL. "Bracket Fatigue evaluation". COMSOL Application Library, 18(3), 1–10, 2014.
[26] Ince A, Glinka G. "A modification of Morrow and Smith-Watson-Topper mean stress correction models". Fatigue & Fracture of Engineering Materials & Structures, 34(10), 805-814, 2011.
[27] Łagoda T, Vantadori S, Głowacka K, Kurek M, Kluger K. "Using the Smith-Watson-Topper parameter and its modifications to calculate the fatigue life of metals: the state-of-the-art". Materials, 15(10), 3481, 2022.
[28] Kamala M, Rahman MM. "Advances in fatigue life modeling: A review". Renewable and Sustainable Energy Reviews, 82, 940-949, 2018.
[29] Karakaş Ö, Tüzün N. "State of the art review of the application of strain energy density in design against fatigue of welded joints". Pamukkale University Journal of Engineering Sciences, 25(4), 462-467, 2019.
[30] Browell R, Hancq A. "Calculating and displaying fatigue results using the ANSYS fatigue module". ANSYS Inc., 2006.
[31] Kınacı BF, Botsalı H, Ozarpa C, Esen İ, Ahlatçı H. "Investigation of fatigue life of draw hook equipment used in freight wagon: Miscellaneous result". Engineering Failure Analysis, 155, 107757, 2024.
[32] Silveira de Santiago R, Possamai TS, Donati DCX, Martins GS de M, Oba R, Tascheck BL, Paiva KV de, Goes Oliveira JL. "Structural behavior and mechanical fatigue of plate and shell heat exchangers through finite element analysis". International Journal of Pressure Vessels and Piping, 210, 105252, 2024.
[33] Zhang Z., Huang C., Xu Z., Yang J., Long S., Tan C., Wan M., Liu D., Ji S., Zeng W. "Influence of notch root radius on high cycle fatigue properties and fatigue crack initiation behavior of Ti-55531 alloy with a multilevel lamellar microstructure." Journal of Materials Research and Technology, 2023, 24, 6293–6311.
[34] Shigley J.E., Mischke C.R., Budynas R.G. "Mechanical Engineering Design". McGraw-Hill, 7th Edition, New York, 2004.
[35] SAE. "Fatigue Design Handbook (SAE J1099)". Society of Automotive Engineers, Warrendale, PA, 1996.
[36] Suresh S. "Fatigue of Materials". Cambridge University Press, 2nd Edition, Cambridge, 1998.
[37] Şirin ŞY. "Sıcak daldırma galvanizleme işleminin ıslah edilmiş ve edilmemiş AISI 4340 çeliğinin yorulma dayanımına etkisi". Pamukkale University Journal of Engineering Sciences, 24(4), 626-634, 2018.