Araştırma Makalesi / Research Paper
Bayburt Üniversitesi Fen Bilimleri Dergisi
Bayburt University Journal of Science

dergipark.gov.tr/bufbd
ISSN: 2667-579X

Cilt 6, Sayı 2, Yıl 2023, Sayfa 151-171
Vol 6, Issue 2, Year 2023, Pages 151-171
doi.org/10.55117/bufbd.1303228

Geliş Tarihi / Date of Recieve: 26.05.2023
Revizyon Tarihi / Date of Revision:13.07.2023
Kabul Tarihi / Date of Acceptance: 11.08.2023

Fatigue Analysis of an Aerospace Elastoplastic Structural Cylindrical Component with Hole under Cyclic Mechanical Load using COMSOL Multiphysics and Taguchi Method Optimization

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Keywords:

Structural design, Elastoplastic behavior, Cylindrical structural components, Finite element analysis (FEA), Fatigue analysis

Abstract

This research study focuses on the fatigue behavior of an aerospace elastoplastic cylindrical structural component with a hole subjected to cyclic mechanical loads. In the demanding operational environment of aerospace applications, the structural components, particularly those with stress concentrators like holes, experience cyclic loading conditions, leading to fatigue failure over time. The key objective of this study is to gain insights into this fatigue behavior and develop an optimized set of design and operational parameters that can enhance the fatigue performance of these components. Utilizing the robust finite element analysis capabilities of COMSOL Multiphysics, a comprehensive model of the elastoplastic cylindrical component is developed. The model captures the intricate effects of the hole, a typical stress raiser, on the fatigue performance under various cyclic mechanical loading conditions. A detailed fatigue analysis is then performed using this model, providing valuable insights into the fatigue life and failure patterns of the component. To enhance the fatigue performance, the Taguchi method, a statistical approach, is employed. This method helps to identify and optimize the key design and operational parameters influencing the fatigue life. The parameters are optimized based on their signal-to-noise ratio, with an aim to maximize the fatigue life and ensure the structural integrity of the component under operational cyclic loads. The findings of this research hold significant implications for the design and manufacturing of aerospace structural components, with potential benefits of improved safety, enhanced durability, and reduced maintenance requirements. However, the results' applicability might be limited by the complexity of real-world operational conditions and the assumptions made in the simulation model. Future studies can validate and enhance these results by incorporating more complex loading scenarios and real-world case studies.

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"Bu makaleye atıf yapmak için:
Erkan TUR, ""Fatigue Analysis of an Aerospace Elastoplastic Structural Cylindrical Component with Hole under Cyclic Mechanical Load using COMSOL Multiphysics and Taguchi Method Optimization"", Bayburt Üniversitesi Fen Bilimleri Dergisi, C. 6, s 1, ss. 151-171

How to cite this article:
Erkan TUR, ""Fatigue Analysis of an Aerospace Elastoplastic Structural Cylindrical Component with Hole under Cyclic Mechanical Load using COMSOL Multiphysics and Taguchi Method Optimization"", Bayburt University Journal of Science, vol. 6, no 2, pp. 151-171

1 INTRODUCTION

The field of aerospace engineering constantly seeks to enhance the reliability and durability of its structural components. One such critical component is the roller bearings or as these can be summarized as elastoplastic cylindrical structure with a hole, typically subjected to repetitive mechanical stress during operations. In such demanding environments, these components may succumb to fatigue failure over time due to the presence of stress concentrators like holes. Fatigue failure is a critical concern in the design and analysis of aerospace structural components, particularly those subjected to cyclic mechanical loading conditions [1]. Such components often exhibit complex behavior due to the presence of stress concentrators, such as holes, which significantly influence their fatigue performance. Understanding the fatigue behavior and optimizing the design and operational parameters are crucial for enhancing the structural integrity and durability of these components. Despite the significant advancements in aerospace design, the issue of fatigue, particularly in structures with stress concentrators, remains an ongoing challenge [2]. The present research focuses on understanding and optimizing the fatigue behavior of these aerospace elastoplastic cylindrical structures under cyclic mechanical loads. This research study aims to investigate the fatigue behavior of an aerospace elastoplastic structural cylindrical component with a hole under cyclic mechanical loads. The focus is on developing a comprehensive understanding of the fatigue mechanisms and failure patterns and employing optimization techniques to identify the key parameters that enhance the fatigue life of the component, and these are applied load and hole diameter of this bearing. [3] reported that these parameters directly affect fatigue life of these structures. To accomplish this objective, the robust finite element analysis capabilities of COMSOL Multiphysics are utilized. COMSOL Multiphysics is a powerful computational tool that allows for the simulation and analysis of complex multiphysics phenomena. In this study, a detailed model of the elastoplastic cylindrical component, considering the intricate effects of the hole as a stress raiser, is developed using COMSOL Multiphysics. The developed model enables the examination of the fatigue performance of the component under various cyclic mechanical loading conditions. By subjecting the component to representative loading scenarios, valuable insights can be gained into the fatigue life and failure patterns. This analysis is essential for understanding the structural behavior and potential failure modes of the component in demanding operational environments. In addition to the fatigue analysis, the Taguchi method, a statistical approach, is employed to optimize the design and operational parameters influencing the fatigue life. The Taguchi method aids in identifying the key parameters and their optimal levels by considering their signal-to-noise ratio [4]. The aim is to maximize the fatigue life of the component and ensure its structural integrity under operational cyclic loads. The findings of this research have significant implications for the design and manufacturing of aerospace structural components. By enhancing the fatigue performance, the safety and durability of these components can be improved, as also reported in [5]. The optimized set of design and operational parameters obtained from this study can guide the development of more reliable and efficient aerospace structural components, leading to reduced maintenance requirements and enhanced operational performance. Leveraging the capabilities of finite element analysis through COMSOL Multiphysics and the statistical optimization capabilities of the Taguchi method, the study aims to develop an optimized set of design and operational parameters. This could significantly enhance the components' fatigue performance, ensuring their structural integrity under operational cyclic loads. However, it is noteworthy that the applicability of the results might be influenced by the complexity of real-world conditions and the assumptions incorporated in the simulation model. Therefore, future studies could focus on validating and improving these results with more intricate loading scenarios and empirical case studies. And it is important to acknowledge that the applicability of the results may be limited by the assumptions made in the simulation model and the complexity of real-world operational conditions. While the developed model captures the essential aspects of the fatigue behavior of the component, incorporating more complex loading scenarios and real-world case studies in future studies would provide further validation and enhance the practical relevance of the findings.

The novelty of this study lies in several key aspects that differentiate it from previous research endeavors. Firstly, this research focuses specifically on the fatigue behavior of an aerospace elastoplastic structural cylindrical component with a hole, the bearings under cyclic mechanical loads. While fatigue analysis has been extensively studied in the aerospace domain, the inclusion of the elastoplastic material behavior and the presence of a stress concentrator like a hole adds complexity to the analysis. This study aims to address this gap in the literature by investigating the intricate effects of these factors on the fatigue performance of the component. Secondly, the utilization of COMSOL Multiphysics as the computational tool for modeling and analysis is noteworthy. COMSOL Multiphysics offers robust finite element analysis capabilities that allow for the simulation of multiphysics phenomena. In this study, the software is employed to develop a comprehensive model that captures the elastoplastic behavior of the cylindrical component, incorporating the stress-raising effects of the hole. This approach enables a detailed examination of the fatigue life and failure patterns of the component under various cyclic mechanical loading conditions. In addition, the implementation of the Taguchi method for optimization contributes to the originality of this study. The Taguchi method is a statistical approach that facilitates the identification and optimization of key design and operational parameters influencing the fatigue life. By considering the signal-to-noise ratio, this method assists in maximizing the fatigue life and ensuring the structural integrity of the component under operational cyclic loads. The incorporation of this optimization technique contributes to a more comprehensive analysis, allowing for the development of an optimized set of parameters that can enhance the fatigue performance of the component. Moreover, the findings of this research have direct implications for the design and manufacturing of aerospace structural components. By gaining insights into the fatigue behavior and identifying the optimized parameters, the safety, durability, and maintenance requirements of these components can be improved. This study, therefore, provides valuable guidance for the development of more reliable and efficient aerospace structural components, potentially reducing costs and enhancing operational performance. Lastly, while previous research has addressed fatigue analysis in aerospace components, this study acknowledges the limitations of the simulation model and real-world operational conditions. The authors emphasize the need for further studies to validate and enhance the results by incorporating more complex loading scenarios and real-world case studies. By acknowledging these limitations and suggesting avenues for future research, this study contributes to the ongoing discourse in the field and provides a foundation for further investigations. In summary, the novelty of this study lies in its focus on the fatigue behavior of an aerospace elastoplastic structural cylindrical component with a hole, the utilization of COMSOL Multiphysics for modeling and analysis, the application of the Taguchi method for optimization, and its direct implications for the design and manufacturing of aerospace structural components. By addressing these aspects, this research adds valuable insights to the existing body of knowledge and paves the way for further advancements in the field of fatigue analysis in aerospace engineering.

Finally, this research study aims to analyze the fatigue behavior of an aerospace elastoplastic structural cylindrical component with a hole under cyclic mechanical loads. By utilizing the advanced finite element analysis capabilities of COMSOL Multiphysics and the optimization techniques of the Taguchi method, this study seeks to improve the fatigue performance of these components. The findings of this research hold substantial potential for enhancing the design, manufacturing, and operational practices in the aerospace industry, contributing to improved safety, durability, and maintenance requirements. Future studies can build upon these findings by considering more complex loading scenarios and real-world case studies to further validate and expand the applicability of the results.

1.1 Literature review

Fatigue analysis of aerospace structural components is a critical aspect of ensuring their structural integrity and reliability. Over the years, extensive research has been conducted to investigate the fatigue behavior of different components and materials under cyclic mechanical loading conditions. This literature review aims to provide an in-depth overview of key findings and advancements in the field, highlighting the relevance and novelty of the present study on the fatigue analysis of an aerospace elastoplastic structural cylindrical component with a hole. Numerous studies have focused on fatigue analysis of metallic materials commonly used in aerospace applications, such as aluminum alloys and titanium alloys. For instance [6] conducted fatigue tests on various metallic and non-metallic aerospace materials, they've found that majority of service failures in aircraft components occur by fatigue and it amounts to about 60% of the total failures, and components with bearing-like components with holes and found that the presence of holes significantly reduced the fatigue life also the stress concentration effect around the holes led to accelerated crack initiation and propagation, resulting in reduced fatigue performance. Similarly, [7] performed fatigue tests on titanium alloy beams with holes and observed similar trends of accelerated crack growth around the holes. These studies highlight the detrimental effect of stress concentrators, such as holes, on the fatigue performance of aerospace components.

In recent years, there has been a growing interest in studying the fatigue behavior of elastoplastic materials. Elastoplastic behavior, characterized by the presence of both elastic and plastic deformation, is common in many aerospace structural components subjected to cyclic loading. [8] conducted fatigue tests on elastoplastic steel specimens and identified the influence of plasticity on the fatigue life. Their findings demonstrated the need to consider elastoplastic behavior in fatigue analysis to accurately predict the fatigue life of components under cyclic loading conditions. To enhance the fatigue performance of aerospace components, optimization techniques have been applied in various studies. The Taguchi method, a statistical approach, has been widely used for optimizing design and operational parameters to improve fatigue life. [9] employed the Taguchi method to optimize the shot peening process parameters of aluminum alloy beams, resulting in enhanced fatigue resistance. This study demonstrated the effectiveness of the Taguchi method in identifying optimal parameters for improved fatigue performance. Finite element analysis (FEA) has been extensively utilized for fatigue analysis of aerospace components. FEA provides a powerful tool for simulating complex structural behaviors and capturing the effects of stress concentrators. Numerous studies have employed FEA to investigate fatigue behavior in aerospace applications. For example, [10] performed FEA on aircraft wing panels with rivet holes under cyclic loading. Their findings revealed the significance of stress concentration factors and crack propagation paths in determining the fatigue life of these components. Despite the existing research on fatigue analysis of aerospace components, the combination of elastoplastic material behavior, the presence of a hole as a stress concentrator, and the utilization of the Taguchi method for optimization in the context of an elastoplastic structural cylindrical component has received limited attention. The present study aims to bridge this research gap by examining the fatigue behavior of such components under cyclic mechanical loads using COMSOL Multiphysics and the Taguchi method. The utilization of COMSOL Multiphysics in fatigue analysis is a notable aspect of this study. COMSOL Multiphysics offers advanced finite element analysis capabilities that allow for comprehensive modeling of multiphysics phenomena. While previous studies have employed FEA, the use of COMSOL Multiphysics provides enhanced accuracy and computational efficiency in simulating the fatigue behavior of the component. It enables the consideration of elastoplastic material behavior and the stress concentration effects of the hole, providing a more realistic representation of the component's fatigue performance. In addition to traditional FEA, other numerical techniques have also been employed in fatigue analysis. For instance, [11] utilized meshless methods, specifically the element-free Galerkin (EFG) method, to investigate the fatigue life of metallic structures with irregular web holes. [12] studied meshless methods for different configurations for holes. Also [13] studied this method of a plate with holes. Their study demonstrated the applicability and accuracy of meshless methods in capturing fatigue crack initiation and propagation around the holes.

Furthermore, the advancements in additive manufacturing (AM) techniques have opened up new possibilities for fatigue analysis in aerospace components. [14] explored the fatigue behavior of AM-built titanium alloy components with holes and found that the presence of holes significantly affected the fatigue life. Their study emphasized the importance of considering AM-specific factors, such as geometric accuracy and microstructural features, in fatigue analysis. The application of the Taguchi method for optimization in the context of fatigue analysis of aerospace components is another novelty of this study. By identifying and optimizing the key parameters influencing fatigue life based on their signal-to-noise ratio, this research aims to enhance the fatigue performance of the component and contribute to the development of more reliable and efficient aerospace structural components. [15] investigated the influence of natural defects on the fatigue resistance of Ti-6Al-4V titanium produced using laser powder bed fusion additive manufacturing. The researchers conducted push-pull fatigue tests on specimens with varying sizes of highly loaded volumes of material to examine the variability in fatigue strength and its sensitivity to defect size. To achieve different sizes of highly loaded volumes, specimens with different numbers of surface hemispherical shape holes with a diameter of 600 μm were tested. The study found that the fatigue damage mechanisms and the average size of natural defects observed on the failure surfaces depended on the size of the highly stressed region. Smaller stressed volumes and defect-free regions exhibited higher fatigue strength. To minimize the impact of lack-of-fusion on fatigue and increase the likelihood of crack initiation from microstructural features, the specimens were built in the horizontal direction. They explored the effect of natural defects on the fatigue resistance of additively manufactured Ti-6Al-4V titanium. It revealed that the size of the highly loaded volume and the presence of defects and holes influenced the fatigue strength and crack initiation behavior. The findings contribute to improving the understanding of fatigue behavior in laser powder bed fusion additive manufacturing and provide insights for enhancing the fatigue performance of additively manufactured components. In recent years, there has been an increasing interest in incorporating machine learning techniques in fatigue analysis. In recent years, fatigue estimations in metals have also been significantly influenced by the implementation of machine learning techniques. [16] employed machine learning algorithms to predict the fatigue life of metallic components under various loading conditions. Their study demonstrated the potential of machine learning models to accurately estimate fatigue life and identify critical features contributing to fatigue failure. Moreover, advancements in multi-scale modeling have provided insights into the microstructural aspects affecting fatigue behavior. [17] conducted multi-scale fatigue analysis of aluminum alloy components with holes, considering the influence of microstructural features and defects. Their study highlighted the importance of microstructural considerations in predicting fatigue life and crack initiation sites. They’ve reported that the anticipated outcomes validate the significance of accounting for the fatigue characteristics of nucleation and propagation of small cracks through distinct deformation mechanisms to enhance the precision of prognosticating the fatigue crack initiation life. To summarize, the literature review underscores the importance of conducting fatigue analysis within the realm of aerospace engineering, specifically in relation to examining the fatigue characteristics of cylindrical structural components with holes that exhibit elastoplastic behavior. The objective of the current investigation is to address this research void through the utilization of COMSOL Multiphysics for precise modeling and the implementation of the Taguchi method for optimization. The present study endeavors to offer significant insights into the fatigue performance of aerospace components by integrating various approaches. The ultimate objective is to contribute towards the advancement of design and operational practices in the aerospace industry.

1.2 Motivation of study

The motivation behind this study stems from the critical importance of fatigue analysis in aerospace engineering. Aerospace structural components, particularly those with stress concentrators like holes, are subjected to cyclic mechanical loading conditions in demanding operational environments. The presence of these stress concentrators significantly affects the fatigue behavior of the components, leading to potential failure over time. Understanding and optimizing the fatigue performance of these components is essential for ensuring their structural integrity, enhancing safety, and reducing maintenance requirements. The motivation to investigate the fatigue behavior of an aerospace elastoplastic structural cylindrical component with a hole arises from the need to address the challenges associated with such components. While previous studies have explored fatigue analysis in aerospace components, the inclusion of elastoplastic material behavior and the presence of stress raisers like holes adds complexity to the analysis. This study aims to fill this gap in the literature by focusing on the intricate effects of these factors on the fatigue performance. The specific choice of utilizing COMSOL Multiphysics as the computational tool is motivated by its advanced finite element analysis capabilities. COMSOL Multiphysics enables the modeling and simulation of complex multiphysics phenomena, allowing for a comprehensive understanding of the fatigue behavior. By utilizing this software, the study aims to capture the elastoplastic behavior of the component and accurately simulate the stress concentration effects of the hole. This modeling approach provides a realistic representation of the component's behavior, leading to more accurate and insightful fatigue analysis results.

Additionally, the motivation behind incorporating the Taguchi method for optimization lies in the desire to enhance the fatigue performance of the component. The Taguchi method is a statistical approach that allows for the identification and optimization of key design and operational parameters [18]. By applying this method, the study seeks to identify the parameters that significantly influence the fatigue life and determine their optimal levels. Optimizing these parameters can lead to an enhanced fatigue performance, ensuring the structural integrity of the component under cyclic loads and potentially reducing maintenance requirements. Furthermore, the practical implications of this research in the aerospace industry motivate the study. Improved fatigue performance of structural components directly translates into enhanced safety, reduced downtime, and lower maintenance costs. By gaining insights into the fatigue behavior and providing an optimized set of design and operational parameters, this study can guide the design and manufacturing processes of aerospace components, leading to more reliable and efficient structures.

In conclusion, the motivation behind this study lies in the need to address the challenges associated with fatigue analysis in aerospace elastoplastic structural components with holes. The desire to understand the intricate effects of stress concentrators and optimize the fatigue performance drives this research. The choice of COMSOL Multiphysics as the computational tool and the application of the Taguchi method add further motivation by providing advanced modeling capabilities and optimization techniques. Ultimately, the study's findings have practical implications for the aerospace industry, contributing to improved safety, reduced maintenance requirements, and enhanced operational performance.

2 MATERIALS AND METHODS

2.1 Theoretical Framework

Metallic structures are commonly exposed to cyclic loading throughout their operational lifetimes. As a result, fatigue mechanisms initiate the formation of microcracks, which subsequently propagate and ultimately lead to structural failure [19]. As a consequence of the imperative need for environmental conservation, it is imperative that metallic structures exhibit an extended service life, thereby necessitating their fatigue life to surpass 107 cycles, which falls under the ultra-high-cycle fatigue life regime [20]. And understanding the underlying theoretical concepts of elastoplasticity, fatigue analysis, finite element analysis (FEA), COMSOL Multiphysics, and the Taguchi method is imperative to this study. These theories form the foundation of the modeling, analysis, and optimization processes that will be employed to study the fatigue behavior of aerospace elastoplastic cylindrical structures under cyclic mechanical load conditions. In Table 1, you can find relevant fatigue and yield models and their calculations, according to Smith Watson Topper model and von Mises [21, 22, 23].

Table 1. Fatigue equations used in analysis

Equation	
Smith Watson-Topper Model	$DP_S = \frac{\Delta\gamma_{eq}}{2}\frac{\Delta\tau'_{eq}}{2}$, where $a = 1 - \frac{1}{3}\vartheta\frac{\sigma_{a,max}}{\sigma'_f}$ and $\beta = \frac{1}{3}\vartheta\frac{\sigma_{a,max}}{\sigma'_f}$
Von Mises	$W = \frac{1}{2}\sigma\epsilon \ and \ U = \iiint_V U_0(x,y,z)dV$

2.2 Elastoplasticity and its importance in aerospace structures

Elastoplasticity is a branch of continuum mechanics that describes the material behavior beyond the elastic limit, wherein the material does not revert to its original form after the removal of the load and undergoes plastic deformation [24]. This behavior is crucial in analyzing structures that are subjected to forces exceeding their elastic limit during their operational lifetime. In aerospace applications, elastoplastic behavior helps determine whether a component can withstand the demanding operational conditions without undergoing permanent deformation. Elastoplasticity, a fundamental material behavior, plays a vital role in the structural performance and design of aerospace components [25]. In aerospace engineering, elastoplasticity refers to the combined elastic and plastic deformation exhibited by materials under loading conditions. Understanding and accurately modeling elastoplastic behavior is crucial for analyzing the response of structures subjected to cyclic mechanical loads, such as those experienced in aerospace applications. Further, understanding elastoplasticity enables engineers to design components with enhanced durability and improved performance under high-stress situations.

2.3 Fatigue analysis

Fatigue analysis is an essential tool used to predict the life of a component subjected to cyclic loading. In an aerospace context, fatigue often becomes a critical mode of failure as the components are subjected to alternating loads, leading to cyclic stress and strain during flight operations. Fatigue analysis helps in predicting the number of cycles a material can withstand before failure, providing valuable insights into the structural life expectancy and maintenance needs. Fatigue failure occurs in three stages: initiation, propagation, and final fracture [26]. The initiation stage involves microscopic damage at the material's stress concentration points, which might be induced by holes in the structure. These microscopic damages gradually grow during the propagation stage until they reach a critical size, leading to final fracture [27, 28].

2.4 Finite element analysis (FEA) and COMSOL Multiphysics

Finite Element Analysis (FEA) is a computational method used to predict how a physical system will react to external forces, vibration, heat, and other physical effects. It divides a larger problem into a series of smaller, simpler parts (finite elements) interconnected at points called nodes. The predictable behavior of each finite element is combined to anticipate the behavior of the entire system. In this study, FEA will be conducted using COMSOL Multiphysics, a simulation software platform capable of solving complex physical problems. It allows for multiphysics coupling, meaning that it can simultaneously solve interconnected physical phenomena—essential for realistic simulation of aerospace components, where structural, thermal, and aerodynamic factors interact.

2.5 Taguchi method

The Taguchi method, developed by Genichi Taguchi, is a statistical method for process optimization and quality control. This method uses design of experiments (DoE) to systematically identify influential factors and optimize processes. Taguchi's method considers both the mean and variability in a process, striving to find optimal conditions that not only produce the desired output but also reduce variability, leading to robust designs [29]. In the context of this research, the Taguchi method will be employed to identify the key operational and design parameters that influence the fatigue life of the elastoplastic cylindrical component and optimize these parameters based on their signal-to-noise ratio. The goal is to maximize the fatigue life and ensure the structural integrity of the component under operational cyclic loads. Each of these theoretical frameworks—elastoplasticity, fatigue analysis, FEA with COMSOL Multiphysics, and the Taguchi method—plays a critical role in this study. The understanding of elastoplastic behavior underlies the behavior of the material under study, while fatigue analysis enables the prediction of the component's life expectancy. Simultaneously, FEA and COMSOL Multiphysics provide the tools necessary to simulate the real-world conditions under which the component operates. Lastly, the Taguchi method offers a systematic and statistical means to optimize the design and operational parameters for improving the fatigue performance of the component. As such, these theories guide the research, analysis, and optimization processes integral to this study. In this study, Minitab software used to design and analyze Taguchi Design of Experiment and also to perform ANOVA. 3-Level design is selected and as the factors, “Applied Load” and “Hole Diameter” are selected. Table 2 represents selected factors and their levels. On Table 3 below, design of experiment parameters for each run is tabulated. Simulations completed regarding DoE Taguchi L9 array.

Table 2. Selected factors and their levels

Factor		**Level**		
		Level 1	Level 2	Level 3
A	Applied Load, MPa	200	600	1000
B	Hole Diameter, mm	2	6	10

Table 3. Taguchi L9 (3^2) orthogonal array

Experiment No.	**A**	**B**
1	200	2
2	200	6
3	200	10
4	600	2
5	600	6
6	600	10
7	1000	2
8	1000	6
9	1000	10

2.6 Analysis of variance (ANOVA)

The Analysis of Variance (ANOVA) method is used to examine the findings of the orthogonal array experiment in order to determine the impact of modifying each component. It is also a useful tool for determining the impact of unconditional variables on a response. The design characteristics that may minimize variance are determined in this research by measuring the degree of variation in the answers using ANOVA. We’ve chosen L9 in the Taguchi approach that address the signal-to-noise ratio. If the signal-to-noise ratio is high, the fatigue life will increase. "Larger the best" is utilized as the optimization criterion for particular performance in this research, whereas "smaller the best" is used as the optimization criteria for plastic strain and Von Mises Strain. Finally, ANOVA analysis is used to establish the contribution ratio for each design parameter. The percentage contribution of each control component may be used to determine the effect of each factor on the performance of the micro-channel heat sink. The Fisher test (F-test) with a 95% confidence level ($P < 0.05$) is used to determine the relevance of different parameters on specific performance, pressure drop, and temperature change. To calculate the F-value for the F-test, the related parameter's variance is compared to the residual variance and evaluated as the mean square of the parameter to the mean square of variance. In Table 4, optimization criterion and their equations are shown. When the F-value is larger than or equal to one, it is frequently used. When the P-value is less than 0.05, the parameter is thought to have a substantial influence on the performance characteristics [30, 31].

Table 4. Optimization criterion

Optimization Criteria	**Equation**
Larger the Best	$\eta = -10\log_{10}(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2})$
Nominal the Best	$\eta = -10\log_{10}(\frac{1}{n}\sum_{i=1}^{n}\frac{\mu^2}{\sigma^2})$
Smaller the Best	$\eta = -10\log_{10}(\frac{1}{n}\sum_{i=1}^{n}{Y_i}^2)$

2.7 Model definition

The model refers to an elastoplastic structural cylindrical component with a hole, which is commonly encountered in aerospace applications. CAD drawing is done using CATIA V5. Simulations designed with Taguchi is done using COMSOL Multiphysics. The component is subjected to multiaxial mechanical load, which induce elastic and plastic deformations. The model aims to accurately describe the behavior of the cylindrical component under these loading conditions, considering the material's elastic and plastic properties. It involves defining the geometric parameters, material properties, and boundary conditions to simulate the component's response. The geometric parameters include the dimensions and shape of the cylindrical component, such as the outer and inner radii, length, and hole diameter. The material properties encompass the elastic modulus, yield strength, ultimate strength, and hardening behavior of the material. Boundary conditions specify the applied loads, constraints, and contact conditions at the hole or any adjoining structures. The model employs appropriate constitutive equations, such as the von Mises yield criterion and associated flow rule, to capture the elastoplastic behavior of the material. Numerical methods, such as finite element analysis or finite difference method, are commonly used to solve the governing equations and obtain the deformation, stress distribution, and plastic strain accumulation within the component. Overall, the model provides a comprehensive understanding of the mechanical behavior of aerospace cylindrical components with holes, enabling engineers to make informed decisions regarding their design, performance, and reliability in demanding aerospace applications. Figure 1 represents the simplified CAD design of roller bearing, and the symmetrical boundaries.

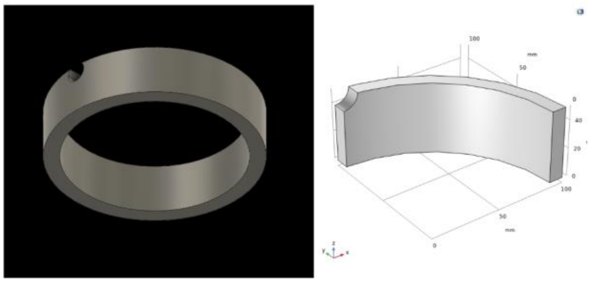

Figure 1. Base CAD design of structural cylindrical component

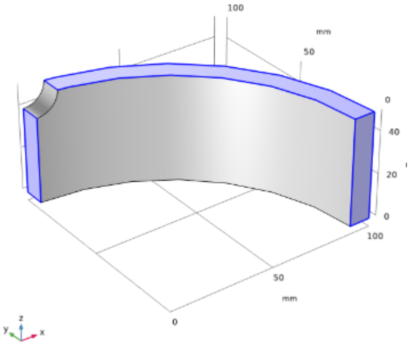

Figure 2. Representations of symmetry boundaries (Detail parts omitted.)

In this study, symmetry boundaries were employed to simplify the geometry and reduce computational resources while preserving the key features of the problem. The symmetry boundaries were applied to the model of the elastoplastic structural cylindrical component with a hole. By assuming symmetry in the geometry, it was possible to analyze only a portion of the component while accurately capturing the behavior of the entire structure. This approach reduced the computational complexity and simulation time required for the analysis. The symmetry boundaries allowed for efficient and effective analysis of the fatigue behavior, providing valuable insights into the performance of the component under cyclic mechanical loads. In Figure 2, representations of symmetry boundaries can be found.

2.8 Meshing

Meshing done with using free tetrahedral, finalized geometry had 1 domain, 7 boundaries, 15 edges and 10 vertices. Figure 3. shows the mesh geometry of base design. Meshing settings can be seen on the Table 5. Mesh consists total of 3102 elements, with minimum mesh quality of 0.2633 and average mesh quality of 0.6941.

Table 5. Meshing Settings in COMSOL

Resolution of Narrow Regions	Maximum Element Size (mm)	Minimum Element Size (mm)	Maximum Element Growth Rate	Curvature Rate
0.5	10	1.8	1.5	0.6

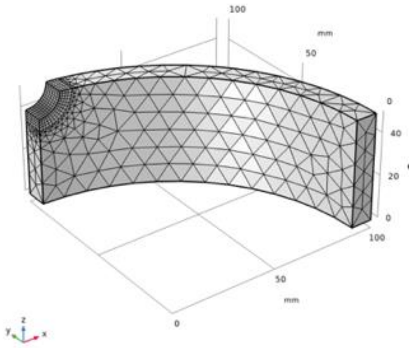

Figure 3. Meshed geometry

2.9 FEA analysis

The present study investigates the response of an aerospace structural element under the influence of multi-axial cyclic loading. When the stresses exceed the yield limit, localized plasticity takes place. A comprehensive elastoplastic simulation of the load cycle is conducted. The Smith-Watson-Topper model, which is stress-based, serves as the foundation for the concept of fatigue. The stress-strain response remains consistent for each successive load cycle. The stability of the second load cycle renders it suitable for utilization in fatigue assessment. The model is subsequently assessed using the SWT model.

Table 6. Elastic and kinematic hardening plasticity properties and fatigue parameters

Elastic Properties	**E, GPa**	**v**		
	997	0.3		
Kinematic Hardening Plasticity Properties	**Yield Stress, MPa**	**Tangent Modulus GPa**		
	210	75		
Fatigue Parameters*	σ_f', MPa	b	ε_f'	d
	1323	-0.097	0.375	-0.60

*Fatigue parameters are used in Smith-Watson-Topper Model.

The present investigation involved the representation of the applied load on a cylindrical structural component with a hole, exhibiting elastoplastic behavior, as a sinusoidal function with respect to time. The utilization of quasi-static load profile is a frequent practice in the emulation of cyclic mechanical loading circumstances, which are widespread in the field of aerospace engineering. The utilization of sinusoidal variation enables a faithful portrayal of the cyclic loading characteristics encountered by the component in its operational settings. The fatigue performance of the component was assessed and the accumulation of damage over time was studied through the application of cyclic loading. The utilization of a sinusoidal load profile facilitated an inquiry into the response of the component to repetitive loading and yielded significant revelations regarding its fatigue characteristics. As the Young's modulus increases, the material exhibits an elevated stress level in its ability to resist elastoplastic deformation when subjected to sinusoidal variated applied load over time. Figure 4 shows the applied load representation in this study to the geometry.

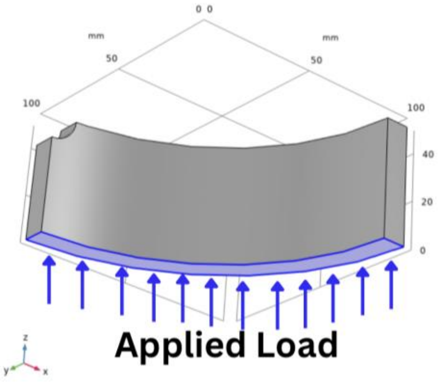

Figure 4. Representation of applied load in COMSOL Multiphysics

3 RESULTS AND DISCUSSION

The findings of this study shed light on the behavior of the component under various loading conditions and provide valuable insights for design optimization, failure prediction, and structural integrity assessment. The logarithm of lifetime in number of cycles (fatigue life) results for the 9 runs conducted in this study provides important insights into the performance of the aerospace elastoplastic structural cylindrical component with a hole under cyclic mechanical loads. By taking the logarithm of the lifetime values, the data is transformed into a more manageable range, facilitating analysis and comparison. The results reveal the variation in fatigue life under different sets of design and operational parameters. Each run represents a specific combination of these parameters, and the corresponding logarithm of the lifetime in number of cycles provides an indication of the component's durability. By examining the range and distribution of the fatigue life results, valuable information can be obtained regarding the influence of different parameter settings on the component's fatigue performance. Analyzing the fatigue life results allows for the identification of trends, patterns, and optimal parameter combinations that enhance the fatigue performance. Statistical analysis techniques, such as mean, standard deviation, and analysis of variance (ANOVA), can be applied to gain further insights into the significance of the design and operational parameters in determining the fatigue life. These results are crucial for optimizing the component's design and operational practices, ensuring enhanced structural integrity and extended service life. Additionally, the logarithm of lifetime results can be used to compare the performance of the component under different loading scenarios. By assessing the relative fatigue life values, the impact of cyclic mechanical loads with varying magnitudes, frequencies, or loading profiles can be evaluated. This information aids in understanding the component's response to different operational conditions and helps in identifying loading scenarios that maximize the fatigue life. Results of the fatigue life for 9 runs can be seen in Figure 5. Upon examining the outcomes of runs 1, 2, and 3, it is evident that the fatigue life is significantly impacted by the diameter of the hole. This pattern is also observable in runs 4, 5, and 6, where an increase in hole diameter results in a decrease in fatigue life. This phenomenon is also observable in sequences of 7, 8, and 9. An examination of runs 1, 2, and 3 with respect to a constant applied load and varying hole diameter reveals that the fatigue life values are as follows: 28000 load cycles for the first run, 9600 load cycles for the second run, and 7200 load cycles for the third run. As reported in [32, 33, 34], it is apparent that an increase in hole diameter results in a decrease in fatigue life, regardless of the applied load. It is important to note that an increase in the applied load has a direct impact on the fatigue life. The observed trend in the data suggests that runs 1, 4, and 7; runs 2, 5 and 8; and runs 3, 6 and 9 can be grouped together based on their consistent diameter size and increasing applied load. The impact of the applied load on the fatigue life of the component is apparent. Specifically, the logarithm of lifetime in run 1 is 28000 load cycles; however, maximum load cycle decreases significantly as the applied load increases. For instance, in run 4, the logarithm of lifetime is 58, and in the 5'th run, it is 9.2 load cycles. Overall, the logarithm of lifetime in number of cycles (fatigue life) results for the all 9 runs provide essential data for assessing the durability and performance of the aerospace elastoplastic structural cylindrical component with a hole. The analysis of these results offers valuable insights into the influence of design and operational parameters, facilitates optimization efforts, and contributes to the development of more reliable and fatigue-resistant aerospace components. Table 7 presents the analysis results of each run alongside their respective logarithmic life values.

Figure 6 represents the accumulated equivalent plastic strain during 2 Load Cycles. The cyclic plastic deformation can be perceived as the impetus for the initiation of a fatigue fracture. The analysis of the accumulated equivalent plastic strain during 2 load cycles for the 9 runs conducted in this study offers valuable insights into the deformation behavior and potential material damage of the aerospace elastoplastic structural cylindrical component with a hole under cyclic mechanical loads. The accumulated equivalent plastic strain is a key indicator of the extent of plastic deformation that the component experiences during the loading cycles. By examining the accumulated equivalent plastic strain values for each run, important information can be gained regarding the component's response to cyclic loading under different sets of design and operational parameters. The analysis allows for the identification of trends and patterns in the distribution of plastic strain, providing insights into the regions of the component that are more susceptible to plastic deformation and potential fatigue failure. The accumulated equivalent plastic strain results can be used to assess the influence of different design and operational parameters on the material's deformation behavior [35]. By comparing the accumulated plastic strain values for different parameter combinations, the impact of variations in parameters such as load magnitude, frequency, or material properties can be evaluated. This information is crucial for optimizing the design and operational practices, allowing for the identification of parameter settings that minimize plastic deformation and improve the component's fatigue resistance [36]. The analysis of the accumulated equivalent plastic strain during 2 load cycles also aids in evaluating the structural integrity of the component. Excessive plastic strain accumulation in critical regions can lead to material damage, such as microstructural changes, crack initiation, or propagation, which can ultimately result in fatigue failure. By identifying regions with high accumulated plastic strain, appropriate mitigation strategies, such as localized strengthening or design modifications, can be implemented to enhance the component's durability and structural integrity. Upon completion of a second load cycle, the stress-strain loop exhibits a repetitive pattern, indicating the attainment of a state of equilibrium. In summary, the analysis of the accumulated equivalent plastic strain during 2 load cycles for the all 9 runs provides valuable information regarding the deformation behavior and potential material damage of the aerospace elastoplastic structural cylindrical component with a hole. The insights gained from this analysis contribute to a better understanding of the component's response to cyclic loading under different parameter combinations. This knowledge is essential for optimizing the design and operational practices, enhancing the component's fatigue resistance, and ensuring its structural integrity in aerospace applications.

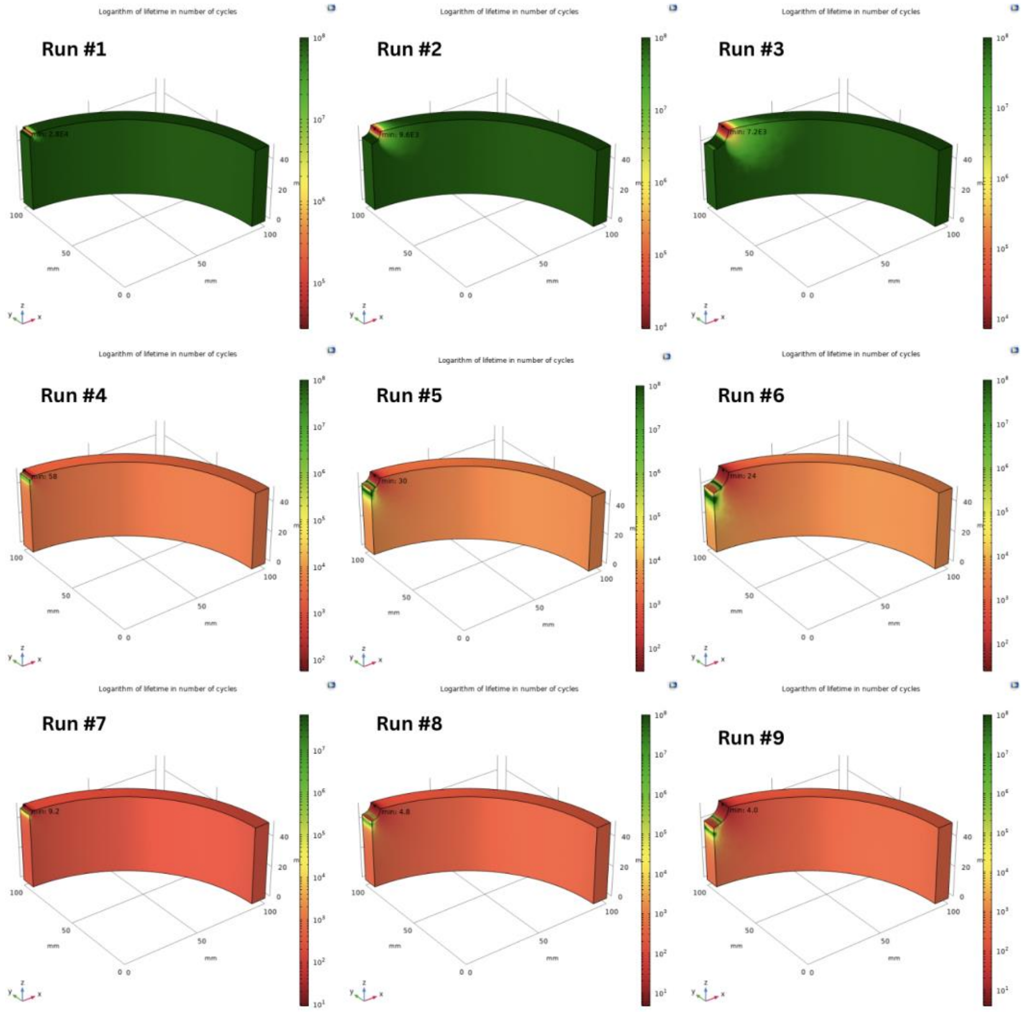

Figure 5. Logarithm of lifetime in number of cycles (Fatigue life) results

Table 7. Logarithm of lifetime in number of cycles results in each run

Experiment No.	Applied Load (MPa)	Hole Diameter (mm)	Logarithm of Lifetime in Number of Cycles
1	200	2	2.8 x 10^4
2	200	6	9.6 x 10^3
3	200	10	7.2 x 10^3
4	600	2	58
5	600	6	30
6	600	10	24
7	1000	2	9.2
8	1000	6	4.8
9	1000	10	4.0

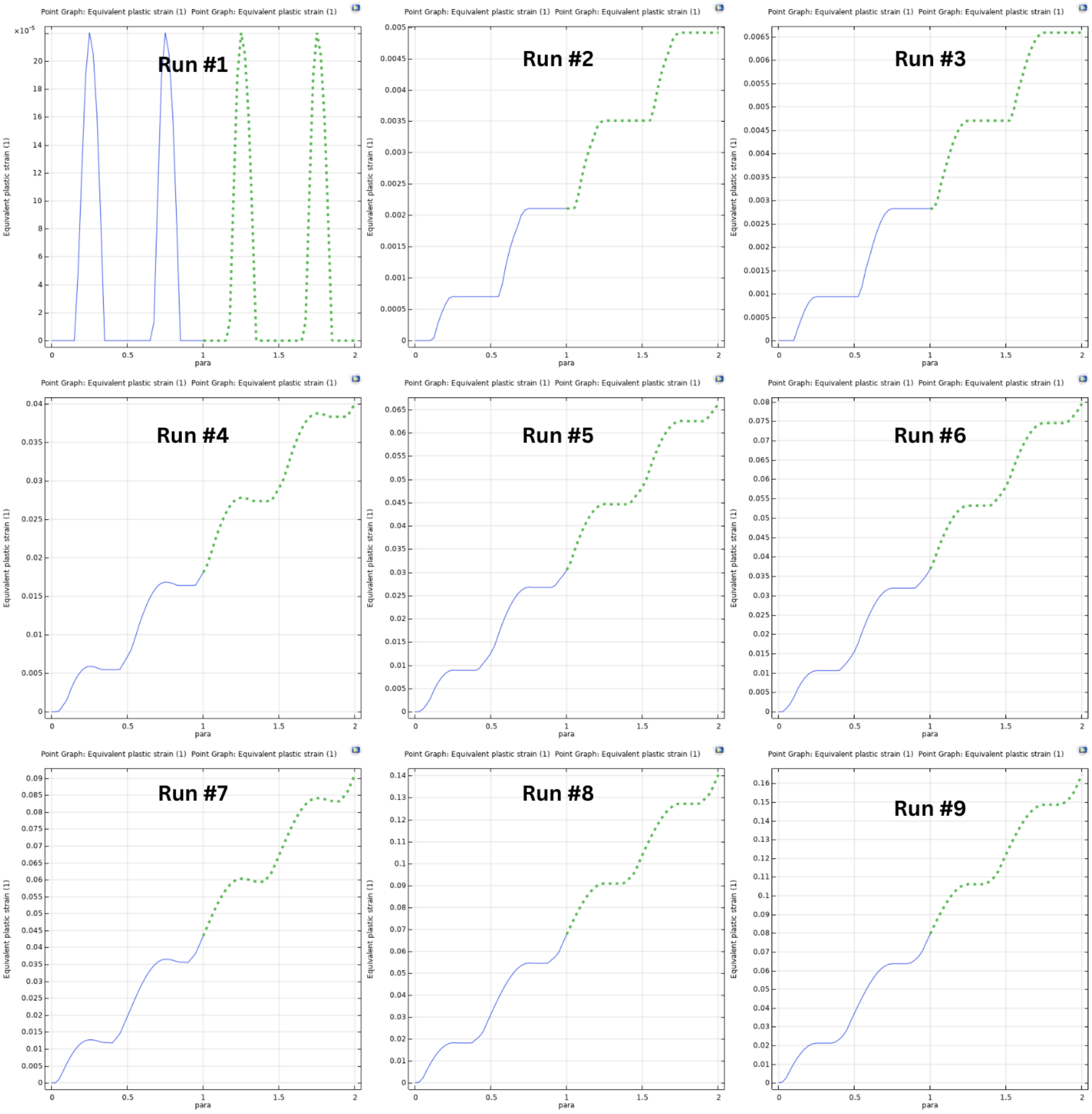

Figure 6. Accumulated equivalent plastic strain during 2 load cycles

Figure 7 represents the von Mises stress levels at the first highest load point. Upon surpassing the yield point, it becomes evident that notable plastic deformations transpire, as depicted in the diagram. The results of the first, second, and third trials indicate that concurrent increases in hole diameter and applied load lead to greater levels of plastic strain. This trend can be observed in the fourth, fifth, and sixth iterations, as well as in the seventh, eighth, and ninth iterations. The analysis of the constant hole diameter and increasing applied load in runs 1-4-7, 2-5-8 and 3-6-9 reveals a direct correlation between the applied load and plastic deformation. The examination of the von Mises stress level during the primary maximum load across the nine trials carried out in this investigation yields significant perspectives on the structural performance and possible failure modes of the aerospace elastoplastic structural cylindrical component featuring a perforation. The von Mises stress is a metric that accounts for the conjoined impact of normal and shear stresses on a given material, serving as an indicator of the material's susceptibility to yielding and plastic deformation. Through an analysis of the von Mises stress level during the initial maximum load in each trial, pertinent data can be gleaned pertaining to the distribution of stress and the specific areas of the component that are subject to notable stress concentrations. The present analysis facilitates the identification of crucial regions that are susceptible to elevated levels of stress, thereby leading to the possibility of material degradation and eventual fatigue fracture. The visual depiction of the von Mises stress level during the initial maximum load across the 9 runs facilitates a comparative analysis of the stress dispersion across various parameter permutations. The aforementioned statement describes the impact of design and operational parameters on the stress state of the component. Through the examination of these graphical representations, one can ascertain the ideal parameter configurations that mitigate stress concentrations and mitigate the likelihood of structural malfunction. The von Mises stress level observed during the initial maximum load is a critical determinant of the structural integrity of the component and its susceptibility to fatigue failure. Elevated levels of stress have the potential to trigger the formation of cracks, which can then propagate during cyclic loading, ultimately resulting in the failure of the component. [37] studied this phenomenon and found that the high stress concentrations lead to lower fatigue life and significant plastic deformation. The examination of stress levels is a valuable tool for evaluating areas of high importance and determining whether design alterations or reinforcement techniques are necessary to improve the component's resistance to fatigue and guarantee its operational dependability. The analysis of the von Mises stress level at the initial maximum load for the 9 runs provides valuable information about the stress distribution and potential failure mechanisms of the aerospace elastoplastic structural cylindrical component with a hole. The graphical representation of these stress levels aids in understanding the influence of different parameter combinations, optimizing design and operational practices, and enhancing the fatigue resistance and structural integrity of the component in aerospace applications.

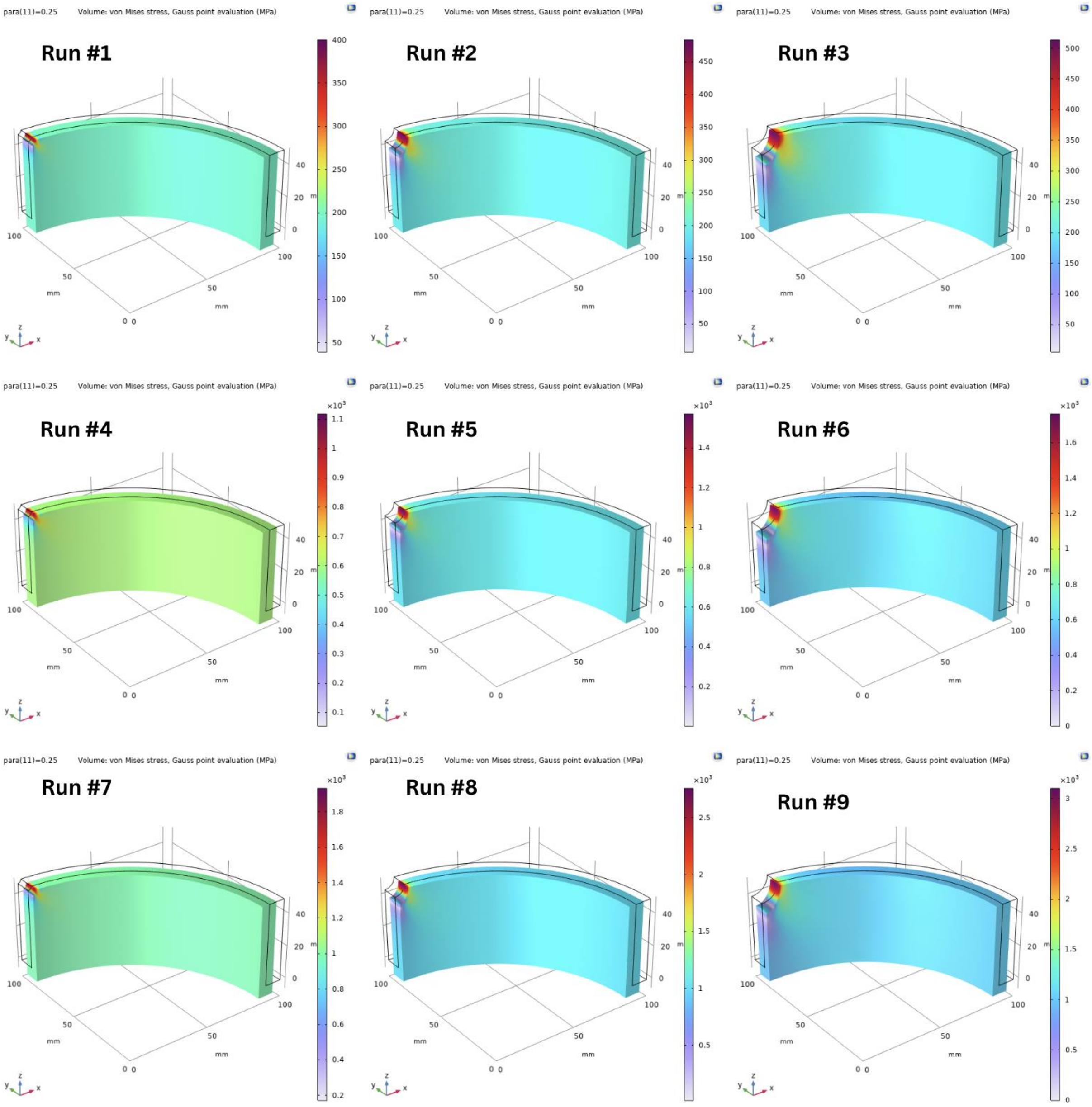

Figure 7. The von Mises Stress level at the initial maximum load

Upon completion of a subsequent load cycle, the stress-strain loop is reiterated, thereby indicating that the process has attained a state of equilibrium. Analysis results for Stress as a Function of Strain during the 1’st Load Cycle is depicted in Figure 8. The analysis of stress as a function of strain during the 1’st load cycle for the 9 runs conducted in this study provides valuable insights into the material behavior and deformation characteristics of the aerospace elastoplastic structural cylindrical component with a hole. By examining the stress-strain relationship, important information can be obtained regarding the component's response to the initial load cycle under different sets of design and operational parameters. This analysis allows for the identification of trends, variations, and potential nonlinearities in the stress-strain curves, indicating the material's elasticity, plasticity, and potential yielding. [38] conducted a research on high fatigue cycles and found that a consistent logarithmic linear correlation exists among the cycles within the initial 90% of the complete cycle duration. Similarly, [39] studied the cycles and found that the observed pattern exhibited a similar loop in first four cycles. It provides crucial data for understanding the component's mechanical behavior and aids in optimizing its design and operational practices for enhanced performance and durability.

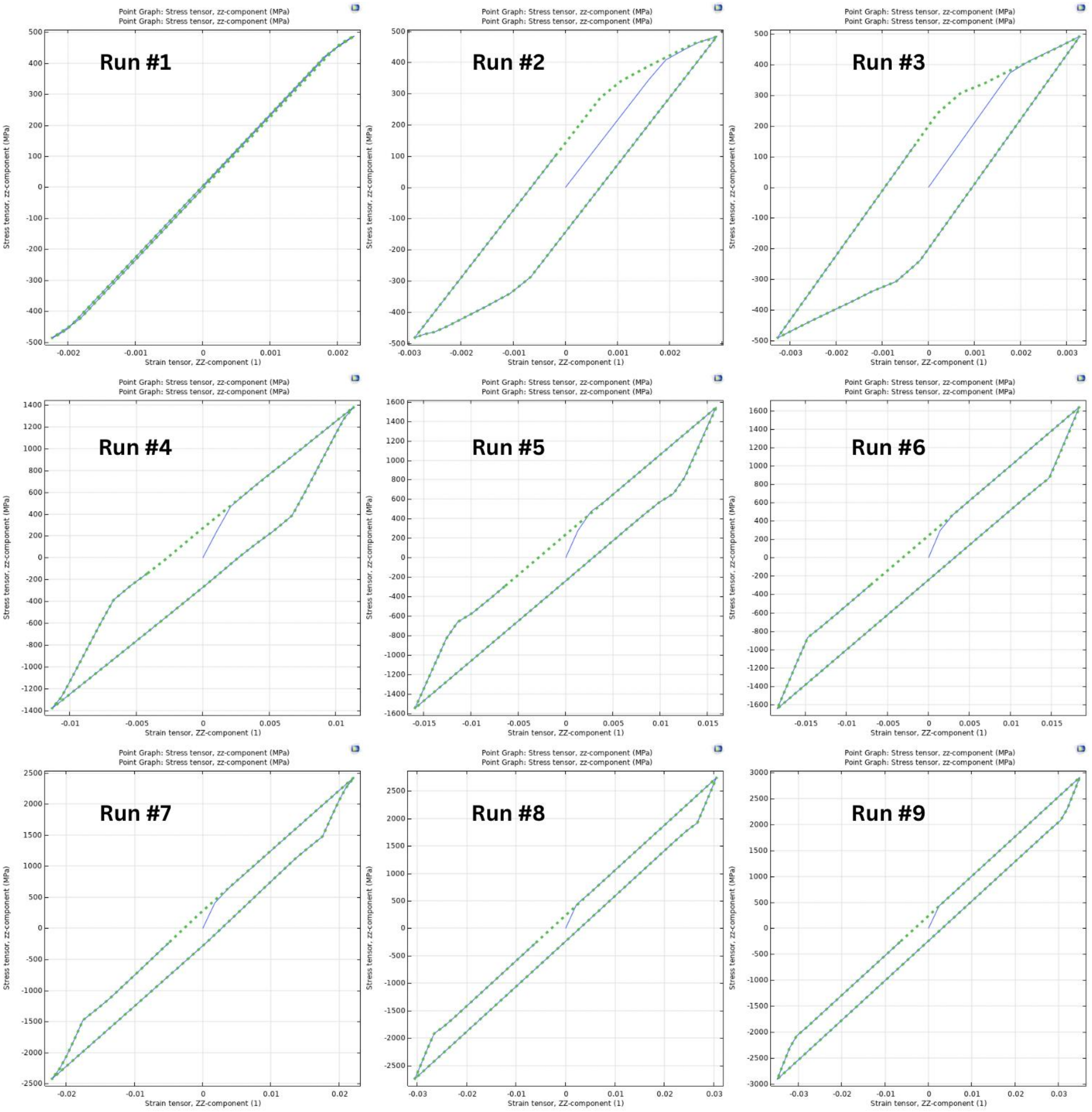

Figure 8. Stress as a function of strain during the 1’st load cycle

3.1 Analysis of S/N ratios

The present investigation employed a methodology wherein superior mechanical performance was anticipated. To this end, the signal-to-noise (S/N) ratios of the mechanical properties under examination were computed utilizing the 'higher the better' approach for fatigue life; ‘smaller the better’ approach is adapted for strain and stress values. Table 8 to 11 displays the outcomes of the mechanical properties that were subjected to experimentation, along with their corresponding mean values and S/N ratios. Meanwhile, the primary impacts of the chosen components are illustrated in Figures 9 through 12. The selection of the optimal level of a controllable factor can be determined by comparing the values of signal-to-noise (S/N) ratios, as it has been established that the highest S/N ratio results in the best quality with minimal variance [40, 41].

In Table 8, response table for means and signal to noise (S/N) Ratios against selected components for fatigue life is shown. In Figure 9, main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for fatigue life is given. able 8 presents the response table for means and signal-to-noise (S/N) ratios against the selected components for fatigue life in this study. The table provides data for the applied load and hole diameter at three different levels. The means represent the average values of the response variable, while the S/N ratios quantify the relationship between the response and the noise level. Figure 9 shows the main effect plots for means and the plots of the response table for S/N ratios against the selected components for fatigue life. The main effect plots illustrate the impact of each component on the means of the response variable. The plots of the response table depict the relationship between the S/N ratios and the selected components, showing how changes in the levels of the components affect the variability of the response variable. From the ANOVA results, it can be observed that increasing the applied load and hole diameter leads to lower means for fatigue life. [42] studies similar occurrence in crack propagation in hole specimens, and found similar results. However, the S/N ratios show variations in the response, indicating the influence of noise factors. The delta values represent the differences between consecutive levels, highlighting the magnitude of change for each component. Based on the ranking, the applied load has a greater impact on the fatigue life compared to the hole diameter.

Table 8. Response table for means and signal to noise (S/N) ratios against selected components for fatigue life

Level	**Means**		**S/N Ratios**	
	Applied Load	**Hole Diameter**	**Applied Load**	**Hole Diameter**
1	53.80	61.62	490.0	1466.7
2	63.71	61.90	1536.7	1530.0
3	68.50	62.49	2670.0	1700.0
Delta	14.70	0.87	2180.0	233.3
Rank	1	2	1	2

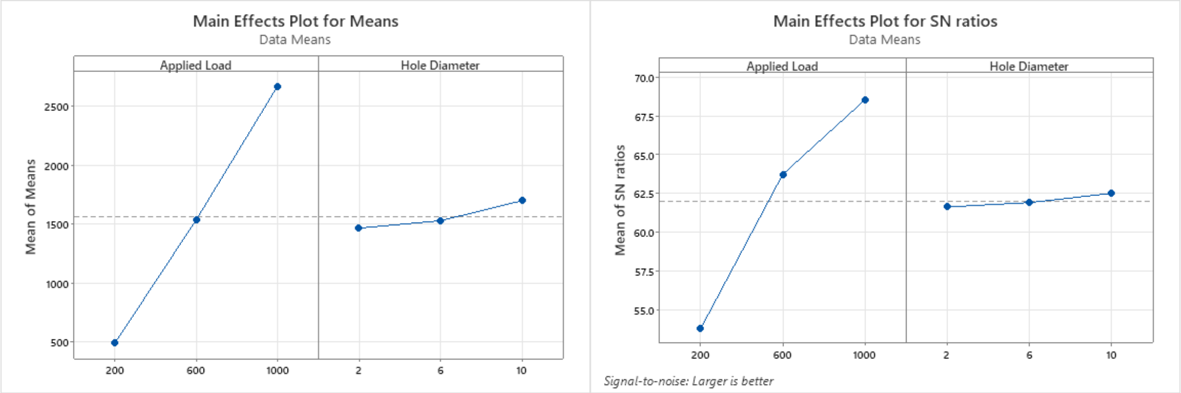

Figure 9. Main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for fatigue life

In Table 9, response table for means and signal to noise (S/N) ratios against selected components for accumulated equivalent plastic strain during 2 load cycles is represented. Figure 10 represents main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for accumulated equivalent plastic strain during 2 load cycles. Table 9 presents the response table for means and signal-to-noise (S/N) ratios against the selected components for the accumulated equivalent plastic strain during 2 load cycles in this study. The table provides data for the applied load and hole diameter at three different levels. The means represent the average values of the response variable, while the S/N ratios quantify the relationship between the response and the noise level. Figure 10 displays the main effect plots for means and the plots of the response table for S/N ratios against the selected components for the accumulated equivalent plastic strain during 2 load cycles. The main effect plots illustrate the impact of each component on the means of the response variable. The plots of the response table depict the relationship between the S/N ratios and the selected components, showing how changes in the levels of the components affect the variability of the response variable. From Table 9, it can be observed that increasing the applied load and hole diameter generally results in higher means for the accumulated equivalent plastic strain during 2 load cycles. The S/N ratios reflect the variations in the response, indicating the influence of noise factors. The delta values represent the differences between consecutive levels, indicating the magnitude of change for each component. Based on the ranking, the applied load has a greater impact on the accumulated equivalent plastic strain compared to the hole diameter.

Table 9. Response table for means and signal to noise (S/N) ratios against selected components for accumulated equivalent plastic strain during 2 load cycles

Level	**Means**		**S/N Ratios**	
	Applied Load	**Hole Diameter**	**Applied Load**	**Hole Diameter**
1	-45.62	-59.32	387.0	4340.7
2	-75.46	-70.97	6173.3	7001.7
3	-82.05	-72.84	13033.3	8251.3
Delta	36.42	13.51	12646.3	3910.7
Rank	1	2	1	2

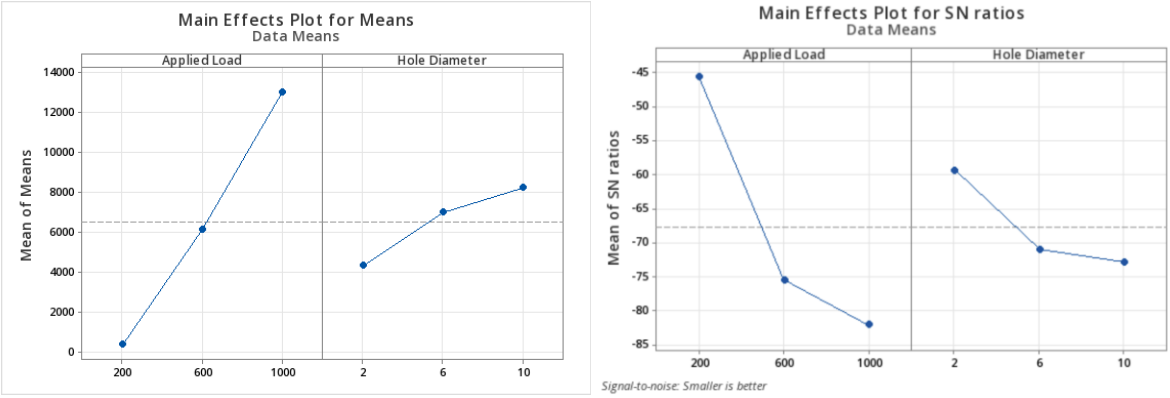

Figure 10. Main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for accumulated equivalent plastic strain during 2 load cycles

Table 10 tabulates response table for means and signal to noise (S/N) ratios against selected components for von Mises stress level at the initial maximum load. Main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for von mises stress level at the initial maximum load is given in Figure 11. Table 10 presents the response table for means and signal-to-noise (S/N) ratios against the selected components for the von Mises stress level at the initial maximum load in this study. The table provides data for the applied load and hole diameter at three different levels. The means represent the average values of the response variable, while the S/N ratios quantify the relationship between the response and the noise level. Figure 11 displays the main effect plots for means and the plots of the response table for S/N ratios against the selected components for the von Mises stress level at the initial maximum load. The main effect plots illustrate the impact of each component on the means of the response variable. The plots of the response table depict the relationship between the S/N ratios and the selected components, showing how changes in the levels of the components affect the variability of the response variable. From the data, it can be observed that increasing the applied load and hole diameter generally leads to higher means for the von Mises stress level at the initial maximum load. The S/N ratios indicate the variations in the response, reflecting the influence of noise factors. The delta values represent the differences between consecutive levels, illustrating the magnitude of change for each component. Based on the ranking, the applied load has a greater impact on the von Mises stress level compared to the hole diameter.

Table 10. Response table for means and signal to noise (S/N) ratios against selected components for von mises stress level at the initial maximum load

Level	**Means**		**S/N Ratios**	
	Applied Load	**Hole Diameter**	**Applied Load**	**Hole Diameter**
1	-45.70	-59.32	390.7	4340.7
2	-75.45	-71.05	6166.7	7000.0
3	-82.21	-72.98	13333.3	8550.0
Delta	36.51	13.65	12942.7	4209.3
Rank	1	2	1	2

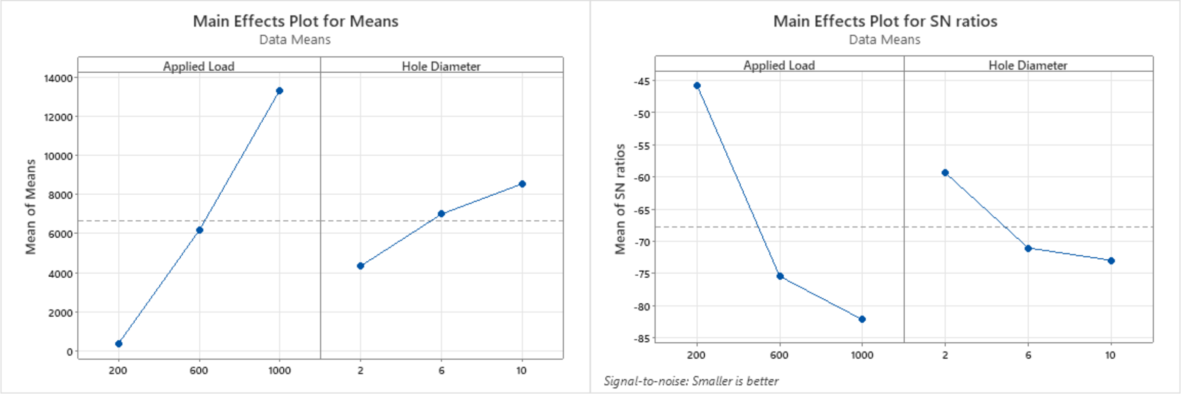

Figure 11. Main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for von mises stress level at the initial maximum load

Table 11 represents the response table for means and signal to noise (S/N) ratios against selected components for stress as a function of strain during the 1'st load cycle. In Figure 12, main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for stress as a function of strain during the 1'st load cycle is given. Table 11 presents the response table for means and signal-to-noise (S/N) ratios against the selected components for stress as a function of strain during the 1st load cycle in this study. The table provides data for the applied load and hole diameter at three different levels. The means represent the average values of the response variable, while the S/N ratios quantify the relationship between the response and the noise level. Figure 12 displays the main effect plots for means and the plots of the response table for S/N ratios against the selected components for stress as a function of strain during the 1st load cycle. The main effect plots illustrate the impact of each component on the means of the response variable. The plots of the response table depict the relationship between the S/N ratios and the selected components, showing how changes in the levels of the components affect the variability of the response variable. ANOVA results indicates that a rise in the applied load results in elevated stress means, whereas the influence of hole diameter on the means is comparatively less significant. The signal-to-noise ratios serve as a measure of the fluctuations in the output, denoting the impact of extraneous factors. The delta values serve to depict the magnitude of change for each component by representing the differences between consecutive levels. The findings indicate that, in terms of stress as a function of strain during the initial load cycle, the applied load exerts a more significant influence than the hole diameter, as per the ranking.

Table 11. Response table for means and signal to noise (S/N) ratios against selected components for stress as a function of strain during the 1'st load cycle

Level	**Means**		**S/N Ratios**	
	Applied Load	**Hole Diameter**	**Applied Load**	**Hole Diameter**
1	487.7	1452.0	-53.76	-61.51
2	1545.3	1592.3	-63.76	-62.12
3	2688.3	1677.0	-68.57	-62.47
Delta	2200.7	225.0	14.81	0.96
Rank	1	2	1	2

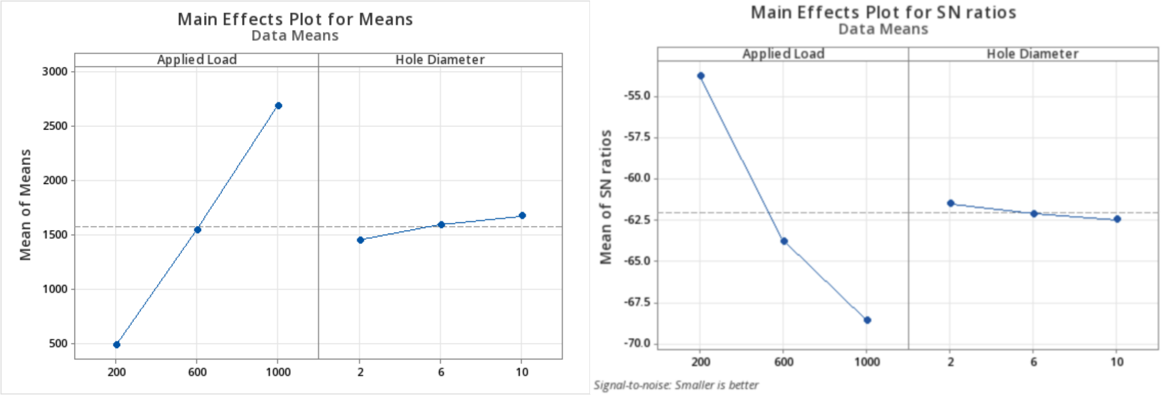

Figure 12. Main effect plots for means and plots of response table for signal to noise (S/N) ratios against selected components for stress as a function of strain during the 1'st load cycle

Figure 9, 10, 11, and 12 demonstrate the significance of the signal-to-noise (S/N) ratios in the analysis of the selected components. The S/N ratios provide valuable insights into the influence of the applied load and hole diameter on the response variables in this study. These figures reveal that both factors are influential, with the applied load being the most significant determining factor across all analyzed results. These findings align with prior research conducted by [43], who investigated the impact of various loading conditions on the fatigue endurance of 18Ni300 steel. Their study indicated that an increase in load magnitude is associated with a higher likelihood of fracture occurrence. This correlation between load magnitude and the likelihood of fracture supports the notion that the applied load plays a critical role in the fatigue behavior of structural components. By utilizing the S/N ratios and considering the prior research, this study acknowledges the importance of optimizing the applied load to enhance the fatigue performance of the aerospace elastoplastic structural cylindrical component with a hole. The findings highlight the need for careful consideration of load magnitude as a key parameter in design and operational practices to mitigate the risk of fracture and improve the component's fatigue life.

4 CONCLUSION

The primary motivation behind conducting this study was to address the critical issue of fatigue failure in aerospace elastoplastic structural cylindrical components with holes under cyclic mechanical loads. In the demanding operational environment of aerospace applications, these components are exposed to significant cyclic loading conditions, which can lead to fatigue failure over time. As such, understanding the fatigue behavior and developing strategies to enhance the fatigue performance of these components is of utmost importance. By performing this study, we aimed to gain valuable insights into the fatigue mechanisms and failure patterns specific to these components. The inclusion of the elastoplastic material behavior and the presence of the stress concentrator, i.e., the hole, added complexity to the analysis. Therefore, our study aimed to address this complexity and provide a comprehensive understanding of the fatigue behavior under various cyclic mechanical loading conditions. Additionally, the utilization of COMSOL Multiphysics as the computational tool allowed us to develop a detailed and accurate model of the component. This model considered the intricate effects of the hole as a stress raiser and captured the elastoplastic behavior, enabling a realistic simulation of the fatigue performance. Moreover, the application of the Taguchi method for optimization was driven by the aim to identify and optimize the key design and operational parameters that influence the fatigue life. By maximizing the fatigue life through parameter optimization, we aimed to ensure the structural integrity of the component under operational cyclic loads. Overall, this study was performed to contribute to the knowledge and understanding of fatigue analysis in aerospace engineering. By providing insights into the fatigue behavior of elastoplastic structural cylindrical components with holes and offering an optimized parameter set, we aimed to improve the design, manufacturing, and operational practices in the aerospace industry, ultimately leading to enhanced safety, durability, and reduced maintenance requirements.

This study presented a comprehensive analysis of the fatigue behavior of an aerospace elastoplastic structural cylindrical component with a hole under cyclic mechanical loads. Through the utilization of COMSOL Multiphysics for finite element analysis and the Taguchi method for optimization, valuable insights were gained into the fatigue life and failure patterns of the component. The results of the fatigue analysis provided a detailed understanding of the deformation, stress distribution, and plastic strain accumulation within the component. The presence of the hole was found to significantly impact the stress concentration and fatigue performance, highlighting the importance of considering stress raisers in the design and analysis process. Moreover, the Taguchi method optimization allowed for the identification of key design and operational parameters that influence the fatigue life of the component. The optimized parameters, such as the applied load and hole diameter, were determined to enhance the fatigue performance and ensure the structural integrity of the component under cyclic mechanical loads. The findings of this study have significant implications for the design and manufacturing of aerospace structures. By incorporating the optimized parameters, engineers can improve the safety, durability, and maintenance requirements of these components. However, it is important to acknowledge that the applicability of the results may be influenced by the assumptions and simplifications made in the simulation model. To further enhance the validity and applicability of the findings, future studies should consider experimental validation and incorporate more complex real-world operational conditions. This would provide a more comprehensive understanding of the fatigue behavior of the component and validate the effectiveness of the optimized parameters. In conclusion, the combination of fatigue analysis using COMSOL Multiphysics and optimization with the Taguchi method offers a valuable approach for improving the fatigue performance of aerospace elastoplastic structural cylindrical components with holes. The insights gained from this study contribute to the advancement of aerospace engineering, ensuring the reliability and structural integrity of components subjected to cyclic mechanical loads. The model accurately predicts the deformation and stress distribution within the cylindrical component under different loading scenarios. The presence of the hole significantly affects the stress concentration, leading to higher stresses around the hole vicinity. This information is crucial for identifying potential failure locations and determining the critical regions that require additional reinforcement or material modifications [44]. The elastoplastic nature of the material is captured by the model, allowing the prediction of plastic strain accumulation during loading. The plastic strain tends to concentrate around the hole edges and regions subjected to high stress levels. By analyzing the plastic strain distribution, engineers can assess the component's resistance to plastic deformation and evaluate its fatigue life under cyclic loading conditions. The model facilitates failure analysis by identifying critical stress levels and locations that may lead to failure initiation. By comparing the predicted stresses with the material's yield and ultimate strengths, engineers can assess the safety margin and determine if the component can withstand the applied loads without experiencing plastic deformation or failure. This information aids in optimizing the design and ensuring the structural integrity of the cylindrical component. The model also enables design optimization by evaluating the effects of different geometric parameters and material properties on the component's performance. Through parametric studies, engineers can assess the influence of varying dimensions, hole sizes, and material characteristics on the stress distribution, deformation, and failure potential. This knowledge facilitates the selection of optimal design configurations that maximize structural strength, minimize weight, and meet the desired performance requirements. By combining the results of deformation, stress distribution, plastic strain accumulation, and failure analysis, the model enables a comprehensive assessment of the structural integrity of the cylindrical component. Engineers can evaluate the component's performance under realistic operating conditions, ensuring that it can withstand the anticipated loads and exhibit sufficient fatigue resistance. This assessment assists in the certification and qualification process for aerospace applications, guaranteeing the component's reliability and safety. Overall, the results obtained from the aerospace elastoplastic structural cylindrical component with a hole model provide valuable insights into the component's behavior, aiding in design optimization and structural integrity assessment. This knowledge contributes to the development of safer and more reliable aerospace structures and supports the advancement of the aerospace industry. These findings provide valuable insights into the relationship between the selected components and the fatigue life of the aerospace elastoplastic structural cylindrical component with a hole. The response table and plots offer a comprehensive understanding of the effects of the components, aiding in the optimization of design and operational parameters to enhance the fatigue performance and durability of the bearing components.

Author Contributions

Erkan TUR: Conceptualization, Methodology, Software, Statistical Analysis, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration

All authors read and approved the final manuscript.

Conflict of interest

No conflict of interest was declared by the authors.

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