



THEORETICAL MODELING AND SIMULATION OF FATIGUE FAILURE IN SUCKER ROD STRING WITH OPTIMIZED THREAD DESIGN FOR ENHANCED FATIGUE RESISTANCE

S. V. Efendi^{*1}, T. S. Suleymanov¹, A. M. Yusubov²

¹Azerbaijan State Oil and Industry University, Baku, Azerbaijan

²SOCAR, Baku, Azerbaijan

ABSTRACT

In this study, the fatigue mechanisms of sucker rod strings were thoroughly examined, leading to the development of an advanced tapered thread design aimed at improving the durability and performance of these essential components in the oil and gas industry. The focus was on analyzing the influence of design, material properties, and operational conditions on fatigue resistance. Detailed simulation results were obtained for the proposed tapered thread geometry, including von Mises stress distribution, fatigue indicator, strain, deformation, and displacement. The results identified the thread root and upper thread region as the critical zones governing the mechanical and fatigue response of the proposed geometry. Using a combination of precise modeling and advanced simulations, the findings demonstrate how the tapered thread geometry effectively distributes mechanical stresses, reducing the potential for crack initiation and propagation. The proposed tapered thread model exhibited greater durability, which is crucial for maintaining reliable valve operation under varying loads and challenging environments. The results demonstrated a favorable mechanical response under the applied loading conditions, highlighting its potential for improved fatigue performance in sucker rod threaded connections. These results provide a numerical basis for further optimization of sucker rod thread geometry and assessment of its fatigue performance under cyclic loading. Experimental validation, quantitative comparison with conventional thread profiles, and fatigue-life assessment using material-specific S–N data are proposed as necessary directions for future research. This research supports the ongoing optimization of sucker rod string technology for demanding operating environments.

Keywords: sucker rod string; fatigue mechanisms; tapered thread design; stress distribution; fatigue resistance.

Date submitted: 06.07.2026

Date accepted: 16.09.2026

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1. Introduction

Sucker rod pumps are one of the most widely used artificial lift systems in the oil and gas industry, primarily deployed in mature wells to enhance hydrocarbon production. These rods operate through a reciprocating motion that lifts fluids to the surface, a process that exposes the mechanical components to cyclic stresses. Over the time, these repetitive stresses can lead to fatigue failure, compromising the pump's reliability, efficiency, and meantime between failures (MTBF). Understanding and mitigating fatigue failure mechanisms in sucker rod pumps is crucial for ensuring operational stability and reducing maintenance costs in oil and gas production [1].

Fatigue failure is a progressive and localized structural damage that occurs when a material is subjected to cyclic loading. It typically initiates at stress concentrators such as cracks, notches, or material defects and propagates over time,

ultimately leading to sudden and catastrophic failures. In the context of sucker rod pumps, fatigue failure is influenced by various factors, including material properties, the amplitude of cyclic stresses, operating conditions, and the design of the pump components.

The aim of this study is to investigate the fatigue failure mechanisms in one of the most critical components of sucker rod pumps, specifically the rod assembly known as the string, using theoretical modeling and simulation. This article will explore the conditions that lead to crack initiation and propagation in sucker rod string, aiming to develop a predictive model that can help to optimize its design and operational conditions. By understanding the key factors influencing fatigue behavior, this study aims to provide insights into improving the reliability and durability of sucker rod string, thereby improving their overall performance in oil and gas extraction.

Fatigue failure in mechanical systems has been a subject of extensive research due to its critical impact on the reliability of oil and gas equipment. Various studies have explored the mechanisms of fatigue damage in materials and their rel-

^{*}E-mail: suleyman.efendy@gmail.com

<http://dx.doi.org/10.5510/OGP20260301233>

evance to different engineering applications, including the oil and gas sector. In the case of sucker rod string, the occurrence of fatigue failure poses a major challenge to the industry's efforts to maintain efficient production levels.

Fatigue failure remains one of the primary challenges in the durability and operational efficiency of sucker rod strings, a critical component in oil and gas extraction systems. These rods operate under cyclic loading conditions due to the continuous reciprocating motion, which inherently subjects them to alternating tensile and compressive stresses [2]. Verifying the complexity of the mechanism involved in fatigue failure of sucker rod strings is vital for improving their reliability and extending their operational lifespan.

The impact of cyclic loading on fatigue behavior is well-established in engineering literature. It has been demonstrated that the cyclic stresses generated by the motion of sucker rods are intensified by factors such as well depth and variable load conditions [3]. These cyclic forces can cause microstructural changes in the rod material, gradually leading to the initiation of fatigue cracks, particularly in regions with high-stress concentration.

This analysis has been extended by identifying geometric discontinuities, such as notches or sharp edges, as focal points for stress concentration that accelerate the onset of crack initiation [4]. These findings emphasize the need to reduce stress concentrators through design optimization in order to strengthen the fatigue life of sucker rod systems.

Further research has highlighted the critical influence of material properties on fatigue resistance. The role of microstructural characteristics has been explored, showing that fine-grained materials exhibit superior fatigue performance due to their ability to distribute stresses more evenly across the structure [5, 6]. This insight is consistent with findings that surface conditions, such as roughness and corrosion, can significantly lower fatigue resistance by serving as sites for micro-crack nucleation [7]. To address these issues, the use of high-strength, corrosion-resistant alloys tailored for sucker rod applications has been investigated, revealing that such materials can notably increase fatigue life, particularly in challenging well conditions where conventional steel rods are more susceptible to damage [8].

Environmental factors, particularly corrosive media and temperature variations, play a substantial role in worsening fatigue damage in sucker rod string. The effects of hydrogen sulfide (H_2S) in oil wells have been studied, demonstrating that corrosion fatigue accelerates crack growth compared to non-corrosive conditions [8]. This aligns with analyses of the influence of temperature fluctuations on fatigue behavior, showing that thermal stresses can increase material degradation and lead to more rapid crack expansion [9]. Building on this, the combined effects of mechanical stress and thermal cycling have been examined, concluding that high temperatures promote crack growth by inducing plastic deformation and weakening the material's structural integrity [10, 11].

The growth of fatigue failure in sucker rods generally follows a three-phase process: crack initiation, crack expansion, and final fracture, consistent with the classical treatment of fatigue and fracture mechanics [12, 13]. Foundational work on crack distribution provides a theoretical basis for understanding how cyclic loads influence crack growth rates [14]. Applying these principles, fracture mechanics models have been used to predict the service life of sucker rod components

under cyclic stresses, highlighting the critical role of stress intensity factors and crack-propagation criteria in determining the rate of crack advancement, similar to observations of crack initiation and early growth reported in high-cycle and very-high-cycle fatigue regimes [15, 16].

In recent years, advanced simulation techniques, such as Finite Element Analysis (FEA), have become invaluable in studying fatigue behavior in mechanical systems. FEA has been employed to model the stress distribution within sucker rods and identify the areas most vulnerable to fatigue damage, offering deeper insight into how modifying cyclic loads could considerably delay crack initiation and growth. Complementing this approach, multi-physics simulations have been incorporated to analyze the interaction between mechanical stress and fluid dynamics, further clarifying the influence of operational parameters, such as pump speed and stroke length, on fatigue performance [4].

Design innovations have also played a pivotal role in reinforcing the durability of sucker rod systems. Tapered rod designs, which gradually distribute stress along the rod length and thereby reduce localized concentrations that lead to fatigue failures, have been investigated, with findings suggesting that such design modifications can substantially improve the mechanical resilience of sucker rods under cyclic loads [17]. This concept has been further expanded through the use of fiber-reinforced composites, which provide a balanced approach to stress distribution and material strain, thereby boosting overall fatigue resistance [18].

Operational best practices and maintenance strategies are equally critical in mitigating fatigue damage. Optimizing stroke length and pump speed can effectively manage the stress levels experienced by sucker rods, thereby extending their service life [19]. The importance of predictive maintenance techniques has further been emphasized, using real-time stress monitoring and data analytics to anticipate failure points and schedule proactive interventions [20, 21]. This approach prevents unexpected breakdowns as well as reduces maintenance costs, ensuring smoother and more efficient operations. The consolidated findings in this area have led to the development of comprehensive design guidelines aimed at minimizing fatigue risks in sucker rod systems, emphasizing material toughness, optimized rod configurations, and the application of advanced surface treatments [17]. These guidelines align with earlier recommendations advocating treatments such as nitriding and shot peening to improve surface hardness and extend the fatigue life of sucker rod components [7].

The fatigue mechanisms in sucker rod pumps are influenced by a complex interplay of cyclic loading conditions, material properties, environmental factors, and design considerations. By incorporating advanced simulation techniques, innovative material advancements, and strategic design improvements, the oil and gas industry can greatly improve the resilience of these critical systems. The insights gathered from this extensive review provide a robust foundation for guiding future innovations in sucker rod string technology, ultimately contributing to more reliable and cost-effective oil-gas production processes. Expanding on the role of material properties in influencing the fatigue life of sucker rod components, it's necessary to note that material selection is a critical factor in the design and longevity of these systems. High-strength steels, such as AISI 4130 and

4140, are favored in the construction of sucker rods because of their excellent combination of tensile strength, hardness, and ductility. These mechanical properties allow the rods to withstand the high cyclic stresses and demanding operational conditions typical of oil and gas extraction processes.

Despite these advantages, high-strength steels are not resistant to fatigue-related issues. Corrosion, in particular, poses a significant threat to the structural integrity of these materials, especially in corrosive environments containing elements like hydrogen sulfide (H_2S) or carbon dioxide (CO_2). Corrosive agents can lead to pitting on the rod surface, which acts as a stress concentrator, initiating micro-cracks that accelerate fatigue failure. Studies have shown that the synergistic effects of mechanical stress and corrosion can drastically reduce the fatigue life of sucker rods, making it a primary concern in material selection [8].

Temperature fluctuations also play a crucial role in fatigue performance. High temperatures can deteriorate the degradation of material properties by increasing oxidation rates and inducing thermal stresses that weaken the rod's microstructure. Research has demonstrated that in high-temperature environments, the fatigue crack growth rate in steels can increase significantly due to the reduced ductility and toughness of the material under such conditions [10].

Advancements in material science have led to the development of corrosion-resistant alloys, such as nickel-based and duplex stainless steels, which offer better performance in aggressive environments. These alloys exhibit improved resistance to both general corrosion and stress corrosion cracking, thereby enhancing the fatigue life of sucker rods under severe conditions [18]. In addition to alloy development, surface treatment techniques such as shot peening, nitriding, and the application of protective coatings have been widely adopted to improve surface hardness and reduce stress concentrations. These treatments create compressive residual stresses on the material's surface, which counterbalance the tensile stresses that promote crack initiation, thereby delaying the onset of fatigue.

Surface coatings, such as tungsten carbide and ceramic-based layers, have proven effective in protecting sucker rods from wear and corrosion. It has been found that such coatings strengthen surface hardness and considerably reduce the frictional forces acting on the rods, which can otherwise contribute to fatigue crack distribution. By combining these surface treatments with corrosion-resistant base materials, the overall durability and service life of sucker rod components can be greatly improved.

2. Stress concentration and fatigue failure in sucker rod threaded connections

In shallow oil well operations, sucker rod pumps are essential components used to lift fluids from the wellbore to the surface. A recurring issue in these systems is the premature fatigue failure of the sucker rod's threaded connections. The connection threads which link individual segments of the rod string are critical points where mechanical stress is distributed during the pump's reciprocating motion. Under cyclic loading conditions, these threaded regions experience alternating tensile and compressive forces, which are intensified by the mechanical dynamics of the unit.

The primary problem lies in the high-stress concentrations that develop around the thread roots. These regions inherently

have geometric discontinuities that act as stress risers, amplifying the localized stress levels compared to the rest of the rod. As a result, even minor imperfections or surface defects in these areas can lead to micro-crack initiation. Over time, these micro-cracks grow into larger fractures due to the continuous cyclic loading, eventually spreading through the material and leading to catastrophic failure of the sucker rod.

Such failures are particularly concerning because they often occur suddenly and without prior warning, resulting in unplanned downtime, costly repairs, and potential production losses in oil and gas industry. The rapid crack spread under cyclic loading conditions is not only influenced by the design of the threads but also by material properties, lubrication conditions, and environmental factors present in the well.

The challenge is compounded by the fact that conventional designs of sucker rod threads have not been adequately optimized to distribute these cyclic stresses evenly. Standard thread profiles often fail to minimize stress concentrations at the root, making them susceptible to fatigue-related damage. As a result, operators frequently encounter unexpected failures, which disrupt the efficiency of oil and gas production.

Addressing this issue requires a comprehensive analysis of the current thread designs and their mechanical behavior under loading condition. Through advanced 3D modeling and finite element analysis (FEA), it's aimed to gain deeper insights into the stress distribution patterns within the threaded connections. By identifying the critical stress points and verifying the factors that contribute to rapid crack growth, optimized thread geometries that distribute stresses more uniformly can be developed which will further strengthen the fatigue resistance of the sucker rods.

The objective of this study is to analyze the root causes of stress concentration and fatigue crack initiation as well as to propose innovative design solutions that can be implemented to extend the service lifecycle of sucker rod string. This will involve evaluating alternative thread profiles, material modifications, and potential surface treatments to reduce the likelihood of fatigue failure. Ultimately, the goal is to increase the reliability and durability of sucker rod string, minimizing the risks associated with thread-induced failures in shallow oil well operations.

The proposed solution focuses on transitioning the sucker rod coupling's thread design to an API Tapered Thread using the UNF (Unified National Fine) series, a standard widely recognized in the oil and gas industry for its superior sealing properties, reinforcing load distribution, and compatibility with existing equipment. This design optimization involves adopting a tapered thread profile that progressively decreases in diameter, ensuring that the threads tighten under load, which provides a more reliable and leak-tight connection essential for high-pressure environments.

The key features of this API Tapered Thread design include a 60-degree thread angle and a fine pitch, which are characteristic of the UNF series. The fine pitch allows for a greater number of threads per inch, resulting in a stronger connection that resists mechanical loosening and advances vibration resistance. By incorporating a smooth transition at the thread root and peak, the design effectively minimizes stress concentrations, thereby improving the fatigue resistance of the coupling. This optimized thread geometry distributes axial loads more evenly as well as minimizes the sharp edges

that could act as stress risers, ultimately leading to an extended service life of the sucker rod under cyclic loading conditions.

Changing to an API tapered thread design based on the UNF (Unified National Fine) thread series aligns the sucker rod coupling with industry standards while providing significant mechanical and operational advantages. The tapered thread profile promotes more uniform load transfer and improves the contact between mating threads, resulting in a mechanically more stable and reliable connection under cyclic loading. The fine thread pitch and optimized thread geometry further reduce stress concentrations at the thread root, enhancing fatigue resistance and enabling the coupling to withstand the repeated loading cycles encountered during sucker rod pumping operations. As a result, the operational service life and reliability of the sucker rod coupling are significantly improved.

Standardizing the sucker rod coupling with UNF series threads in compliance with API guidelines improves its performance characteristics, ensures compatibility with a wide array of existing oilfield equipment. This alignment with industry standards simplifies the maintenance and replacement processes, leading to reduced downtime and lower operational costs, which are crucial factors in the efficiency-driven oil and gas sector.

Figure 1 illustrates the proposed API Tapered Thread (UNF series) design, highlighting the tapered profile, thread angle, and dimensions that play a pivotal role in enhancing both the mechanical properties and the sealing capabilities of the sucker rod coupling. This visual aid emphasizes how the design modifications contribute to a more robust, durable, and industry-compatible solution.

The proposed renewal of the thread design to an API Tapered Thread using the UNF (Unified National Fine) series warrants a comprehensive comparison between these two thread types to understand their suitability for oil and gas applications. API threads and UNF threads have distinct characteristics, each customized to specific mechanical and industrial needs.

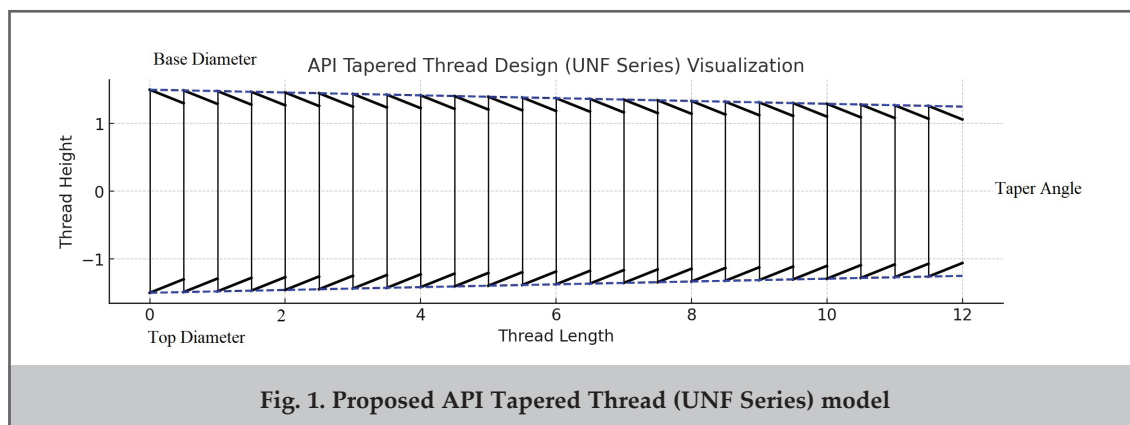
API threads are specifically engineered for the oil and gas industry and are standardized by the American Petroleum Institute. These threads are predominantly used in applications such as casing, tubing, drill pipes, and sucker rods. A key feature of API threads is their tapered profile, which means the thread diameter decreases along its length, creating a tighter fit as the joint is torqued. This tapering is essential for creating a self-sealing effect, which is crucial in preventing fluid leaks in high-pressure environments

typically found in oil well operations. The tapered design ensures that as the threads are tightened, they compress more tightly against each other, greatly improving the connection's integrity under load. In contrast, UNF threads belong to the Unified Thread Standard and are widely used in mechanical industries. They feature a parallel profile, where the thread's diameter remains constant along its length. This design provides uniform engagement with the mating part, which is ideal for applications that require precise adjustments and resistance to vibration. The UNF threads have a fine pitch, meaning there are more threads per inch compared to rougher threads, which increases their tensile load capacity and ability to maintain a secure connection under dynamic conditions.

The applications of API threads are primarily within the oil and gas sector, where their ability to withstand extreme pressures and cyclical stresses is crucial. They are extensively used in downhole tools and connections, providing reliability and robustness in production operations. Conversely, UNF threads are more commonly found in industries such as automotive, aerospace, and precision machinery, where their fine thread pitch is valued for its ability to handle precise mechanical adjustments and resist loosening under vibration. The primary advantage of API threads lies in their ability to create a secure, self-sealing connection that prevents leaks in high-pressure conditions, which is not inherently possible with UNF threads. This makes API threads the preferred choice in applications where maintaining the integrity of the connection is critical. In contrast, the UNF threads, with their fine pitch, excel in delivering higher tensile strength and are ideal for mechanical assemblies that require tight and precise fitting, even though they might not provide the same level of leak resistance without supplementary sealing (table 1).

By adopting the API Tapered Thread (UNF series) design, the sucker rod coupling achieves significant advancements in both its mechanical performance and longevity. The refined thread geometry, characterized by smooth root and crest transitions, not only extends the coupling's fatigue life but also ensures a high level of sealing efficiency necessary for modern oilfield operations. Standardizing this design according to widely accepted industry specifications offers a dual benefit: it improves the mechanical integrity of the connection and ensures seamless integration with existing components, thus reducing maintenance costs and operational interruptions.

In overall, the transition to the API Tapered Thread (UNF series) provides a superior solution for the coupling of the sucker rod by offering strengthened sealing properties,



Technical specifications of the proposed thread model		Table 1
Parameter	Technical specification	
Thread type	API Tapered Thread (UNF Series)	
Thread angle (flank angle)	60 degrees (standard for UNF threads)	
Taper rate	1:16 (typical API taper specification)	
Major diameter	3.5 inches (variable depending on rod size)	
Minor diameter	3.0 inches (at thread root, depends on rod size)	
Pitch	0.05 inches (20 threads per inch, typical UNF specification)	
Lead	Equal to the pitch for single-start threads (0.05 inches)	
Root radius	0.05 inches (optimized for stress reduction)	
Crest radius	0.02 inches (smoother transition to reduce stress concentration)	
Thread height	0.25 inches (depth from crest to root)	
Thread engagement length	8 inches (ensures maximum load transfer)	
Material specification	High-strength steel alloy (e.g., AISI 4140 or 4340)	
Maximum tensile load capacity	Up to 150,000 psi (dependent on material and thread size)	
Torque range	1200 - 1500 lb-ft (for secure joint tightening)	
Sealing mechanism	Metal-to-metal contact enhanced by taper for leak-proof seal	
Standard compliance	API 5B, API 7-2 (for thread dimensions and tolerances)	

improved fatigue resistance and compliance with industry standards. This design aligns with best practices in equipment manufacturing, optimizes the durability and reliability of sucker rod couplings, making it a preferred choice for oil and gas industry that demand high performance under challenging conditions.

3. Analysis and 3D simulation of fatigue resistance in proposed tapered thread

3.1. Calculation of stress concentration for the proposed tapered thread

Stress concentration refers to the localized increase in stress that occurs at geometric discontinuities such as notches, holes, or thread roots. In threaded connections like the API Tapered Thread (UNF series), the thread root acts as a critical stress riser, where the stress distribution is not uniform. This concentration of stress necessarily impacts the fatigue life of the connection, making it essential to accurately assess the stress concentration factor for fatigue analysis. Before proceeding with the calculations, it is important to define the parameters that influence stress concentration in the thread design which are as per following:

- Root radius (r): The bend at the base of the thread. A larger root radius typically leads to a lower stress concentration.
- Thread depth (h): The vertical distance from the crest to the root of the thread. Greater thread depth increases the load-bearing capability but may also influence stress distribution.
- Nominal stress (σ_{nom}): The average or nominal stress that would be present if the thread geometry were not present.
- Notch sensitivity factor (q): A material-specific factor that quantifies how sensitive the material is to notches or geometric discontinuities.
- Theoretical stress concentration factor (α): Represents the stress concentration for a sharp notch without considering material properties.

The stress concentration factor – quantifies the increase in stress at the root of the thread compared to the nominal stress. It is calculated using Peterson's formula for notched elements:

$$K_t = 1 + q \left(\frac{\alpha}{\sqrt{r/h}} \right)$$

where q – represents the notch sensitivity of the material, typically ranging from 0 (not sensitive) to 1 (fully sensitive); α – theoretical stress concentration factor for an ideal sharp notch, usually between 2 and 3 for typical thread geometries; r – root radius of the thread, which affects the level of stress concentration; h – thread depth, impacting the load distribution and stress levels.

For this analysis, following values are considered which are typical for API Tapered Threads (table 2).

Using above values, the ratio of root radius to thread depth can be calculated as per following:

$$\frac{r}{h} = \frac{0.05}{0.25} = 0.2$$

This ratio indicates the relative size of the root radius compared to the depth of the thread.

Square root of the ratio can be calculated as per following:

$$\sqrt{r/h} = \sqrt{0.2} \approx 0.0447$$

Technical parameters for calculation of the stress concentration of proposed thread model		Table 2
Root radius (r)	0.05 inches	
Thread depth (h):	0.25 inches	
Notch sensitivity factor (q)	0.85 (assuming high-strength steel – AISI 4140)	
Theoretical stress concentration factor (α)	2.5 (based on standard thread profiles)	

The square root of the ratio is used to moderate the effect of the thread's geometry on the stress concentration.

Compute the stress contribution from the theoretical factor can be computed as per following from the given details in table above. Multiply the theoretical stress concentration factor by the square root of the ratio:

$$\frac{\alpha}{\sqrt{r/h}} = \frac{2.5}{\sqrt{0.447}} \approx 5.59$$

This value represents the geometric influence on the stress concentration in the absence of material considerations.

Apply the Notch Sensitivity Factor: Incorporate the notch sensitivity of the material using the factor q :

$$q \left(\frac{\alpha}{\sqrt{r/h}} \right) = 0.85 \times 5.59 \approx 4.75$$

This step adjusts the stress concentration based on the material's response to geometric discontinuities.

Final calculation of the stress concentration Factor will be run as per following:

$$K_t = 1 + 4.75 = 5.75$$

The calculated stress concentration factor is approximately 5.75, indicating that the stress at the thread root is amplified by this factor compared to the nominal stress.

The stress concentration factor of 5.75 signifies that the localized stress at the thread root is nearly six times higher than the nominal stress. This amplification can mainly influence the fatigue life of the thread, as areas with higher stress concentrations are more susceptible to crack initiation and distribution under cyclic loading. Reducing the root radius or increasing the thread's root curvature could further lower this factor, thereby enhancing the fatigue resistance. The calculated K_t value is critical for fatigue analysis because it provides insight into the potential for crack initiation at the thread root. A high stress concentration factor implies that even moderate cyclic loads can lead to material fatigue, resulting in cracks that grow over time. Engineering strategies to mitigate these stress concentrations include optimizing the thread design by increasing the root radius or applying surface treatments like shot peening to cause compressive residual stresses at the thread root.

Increasing the root radius leads to a smoother stress distribution, dramatically lowering the stress concentration factor. Surface treatment techniques, such as shot peening and carburizing, can introduce compressive residual stress-

es, which improves the material's resistance to fatigue. Additionally, selecting high-toughness materials can reduce the sensitivity of threads to stress concentrations, thereby extending their fatigue life.

The detailed calculation of the stress concentration factor for the API Tapered Thread (UNF series) highlights the importance of geometric optimization in improving the fatigue resistance of threaded connections. By verifying and mitigating stress concentrations, the mechanical reliability of sucker rod couplings can be further developed and improved, leading to more durable and longer-lasting components in oil and gas industry.

3.2. Simulation of fatigue resistance in proposed tapered thread

The three-dimensional finite element model was developed to evaluate the mechanical response of the proposed tapered thread geometry. The material was represented as high-strength steel corresponding to the AISI 4140 class. The threaded component was subjected to an axial mechanical loading condition, while the opposite end of the model was constrained to represent the load-transfer condition of the threaded connection. The mesh was generated over the complete three-dimensional geometry with local refinement in the thread-root and thread-transition regions, where high stress gradients are expected. The stress, strain, deformation, displacement, and fatigue-indicator fields were subsequently evaluated over the modeled geometry. The main finite element modeling parameters are summarized in table 3.

Figure 2 presents the 3D von Mises stress distribution on a tapered thread model, illustrating how stress is distributed throughout the conical structure under mechanical loading. In the visualization, the thread's geometry is represented in a gradient color scale, transitioning from blue to red. The blue regions signify areas of lower stress, while the red areas indicate higher stress concentrations.

The results show that the highest stress levels occur at the top of the tapered thread, where the color shifts to a bright red. This indicates that the top region of the thread is under stress and represents the critical area most susceptible to material deformation or failure. The stress levels gradually decrease toward the base of the cone, represented in blue, suggesting that the lower parts of the thread experience minimal stress. This gradient highlights the stress distribution characteristics of the proposed tapered thread geometry.

The tapering in the thread design plays a crucial role in minimizing stress concentrations by allowing the load

FEA modeling parameters of the proposed tapered thread

Table 3

Parameter	Specification
Model geometry	3D solid model of the proposed tapered thread
Material	AISI 4140 high-strength steel
Material properties	Young's modulus: 205 GPa; Poisson's ratio: 0.29
Loading	Axial mechanical loading
Boundary condition	Opposite end constrained
Mesh	3D finite element mesh with local refinement at thread-root and thread-transition regions
Local mesh refinement	Thread-root and thread-transition regions
Evaluated parameters	Von Mises stress, fatigue indicator, strain, deformation and displacement

to transition smoothly along the length of the thread. This helps in reducing localized stresses that could lead to material fatigue or crack initiation. The simulation indicates that the proposed tapered thread geometry provides a favorable stress distribution along the modeled structure.

The von Mises stress distribution clearly identifies the regions of the thread that are most vulnerable to mechanical loading, with the highest concentration of stress located near the top. This information is vital for predicting potential failure points and optimizing the design of the threaded connection to improve its performance under cyclic and static loads. The tapered thread's ability to distribute stress effectively validates its suitability for high-stress applications, such as those encountered in the oil and gas industry.

Figure 3 illustrates the 3D fatigue analysis of a tapered thread model. In this visualization, the color gradient transitions from purple to yellow, representing the fatigue indicator values distributed across the conical structure. Fatigue analysis focuses on predicting how the thread material will behave under repeated cyclic loading, which is crucial for assessing the durability and life prediction of the threaded connection.

The model shows that the highest fatigue indicator values are located near the base of the tapered thread, where the color shifts to yellow. This suggests that this region is most susceptible to fatigue damage due to the repeated stress cycles it experiences during operation. As it moves toward the top of the thread, the color gradually transitions to purple, indicating lower fatigue levels in this region. The tapering design effectively reduces the concentration of cyclic stresses as it progresses towards the upper sections of the thread.

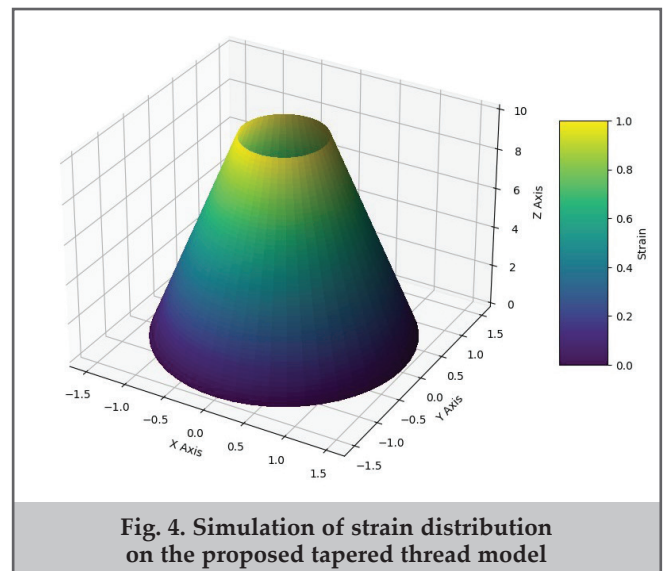
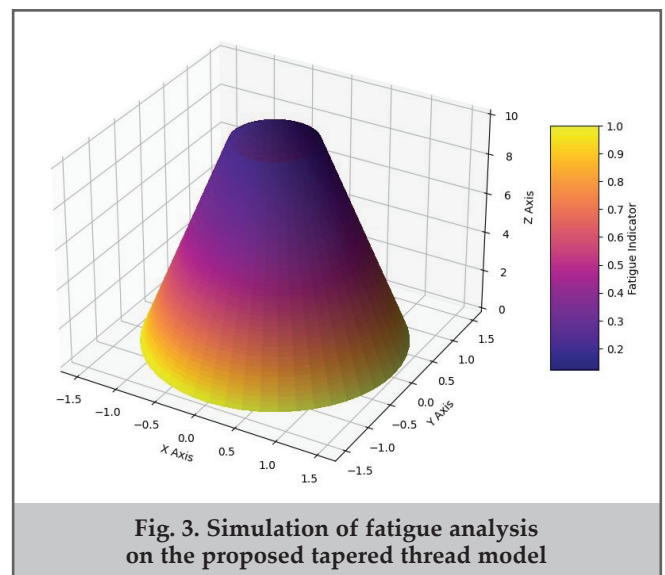
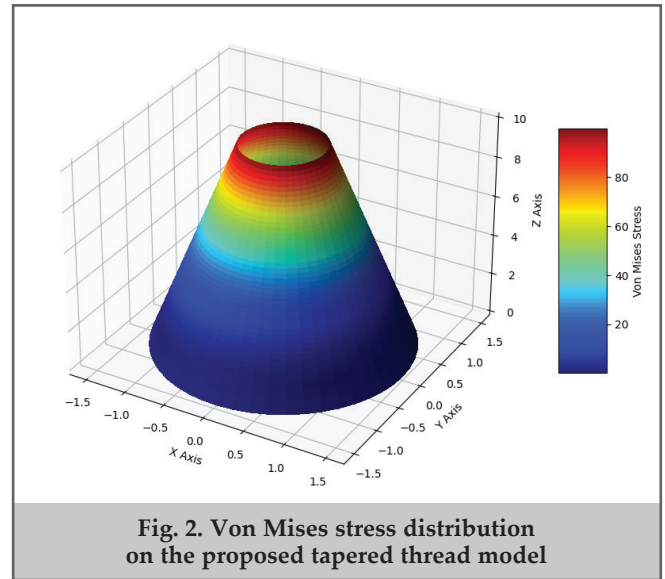
The results of the simulation indicate that the tapered thread's geometry plays a vital role in distributing the cyclic stresses more evenly across its surface. The tapering helps to ease stress concentration, particularly in the upper areas of the thread, thereby minimizing the risk of crack initiation and distribution. However, the base remains a critical zone where the accumulation of stress cycles can lead to potential fatigue failures over time.

In conclusion, the fatigue analysis highlights the areas most prone to material degradation under repeated loading conditions. The yellow regions at the base of the thread signal a need for careful consideration in design optimization to enhance the thread's resistance to cyclic fatigue. Understanding these critical zones allows for better material selection and design improvements, ultimately extending the lifetime of the threaded connection in demanding applications.

Figure 4 illustrates the 3D strain distribution on a tapered thread model, visualizing how the thread deforms under an applied load. The color gradient in this visualization ranges from purple to yellow, indicating the magnitude of the strain experienced by different regions of the thread. Strain measures how much the material stretches or compresses in response to stress, providing crucial insights into its deformation behavior.

The highest strain levels are observed near the top of the tapered thread, where the color transitions to yellow. This indicates that this area undergoes the most significant deformation under the applied load. The base of the thread, represented in purple, experiences considerably lower strain, suggesting that

it remains relatively stable with minimal deformation. This distribution pattern highlights how the tapered thread design directs most of the deformation to the upper regions while maintaining structural integrity at the base.



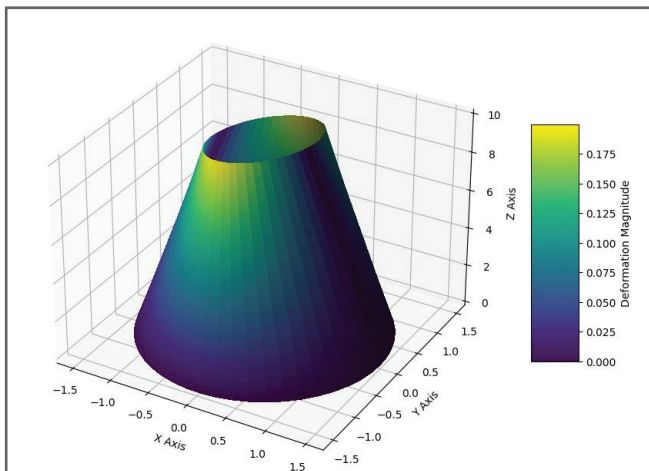


Fig. 5. Simulation of proposed tapered thread deformation under external loading conditions

The results indicate that the tapered geometry of the thread plays an essential role in controlling the strain distribution, allowing for more flexibility at the top while reducing deformation at the lower sections. This characteristic is beneficial for applications where localized flexibility is required to absorb stress while ensuring the thread's base remains strong and secure. The gradual change in strain levels also helps prevent sudden failure by distributing the load more evenly throughout the structure.

In overall, the strain distribution analysis reveals that the tapered thread design effectively manages deformation under load, concentrating it in the upper regions while protecting the base from excessive strain. This insight is essential for optimizing the thread's mechanical performance, enabling it to withstand varying loads without compromising its structural stability. Understanding these deformation patterns guides improvements in thread design, ensuring durability and efficiency in practical applications.

Figure 5 demonstrates the 3D visualization of tapered thread deformation under an external load, illustrating how the thread structure physically shifts in response to the applied force. The color map ranges from purple to yellow, representing the magnitude of deformation across different sections of the thread. Deformation magnitude is a measure of how much the material's shape changes under the influence of mechanical stress.

The highest deformation levels are seen at the top of the thread, where the color transitions to yellow, indicating that this region experiences the most significant movement. As the visualization moves toward the base of the thread, the color shifts to purple, signifying lower levels of deformation. This distribution pattern suggests that the upper portion of the thread is more flexible and capable of adapting to external forces, while the base remains relatively stable and rigid.

These results confirm that the tapered design of the thread effectively localizes deformation to specific areas, allowing it to absorb and distribute external forces without compromising the integrity of the entire structure. The conical shape ensures that most of the stress is managed by the upper part of the thread, while the base provides a strong support that resists significant movement. This controlled deformation is crucial for preventing structural failures and maintaining the thread's performance under dynamic loading conditions.

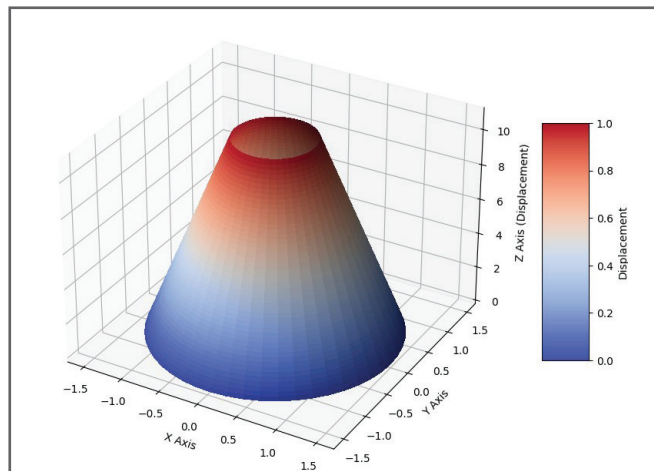


Fig. 6. Displacement analysis on a proposed tapered thread model

In summary, the deformation analysis highlights the benefits of the tapered thread design in managing mechanical stress. By concentrating deformation in the upper regions and protecting the lower sections, the thread can endure greater external forces without losing its mechanical properties or stability. This insight is valuable for optimizing thread designs in applications that require both flexibility and structural endurance, ensuring that the components can withstand varying operational demands.

Figure 6 showcases the 3D displacement analysis on a tapered thread model, highlighting how different sections of the thread move in response to applied forces. The color gradient used in this visualization transitions from blue to red, representing the magnitude of displacement experienced by the thread. Displacement refers to the degree to which points in the thread move from their original position under the influence of external loads.

In the visualization, the highest displacement levels are seen at the top of the thread, where the color shifts to red. This indicates that the upper part of the thread undergoes the most significant movement when subjected to stress. In contrast, the lower sections of the thread, described in blue, show minimal displacement, suggesting that the base of the thread remains relatively fixed and stable.

The displacement pattern reveals the tapered thread's ability to concentrate flexibility at its upper regions while maintaining a strong and secure foundation at its base. This characteristic is advantageous in practical applications, as it allows the upper part of the thread to absorb external forces more effectively while ensuring that the lower portion remains supported, providing structural support. The gradual transition from low displacement at the base to high displacement at the top indicates a smooth distribution of forces, reducing the risk of abrupt failures.

Thus, the displacement analysis of the tapered thread model demonstrates its effectiveness in managing structural shifts under load. By directing the displacement primarily to the upper areas, the thread design helps to dissipate the energy of external forces without compromising the overall integrity of the structure. This insight is essential for optimizing threaded connections, ensuring they can endure mechanical loads while maintaining their stability and reliability in various industrial applications.

Conclusions

This study investigated the fatigue behavior of sucker rod threaded connections with particular emphasis on stress concentration and the influence of thread geometry. A tapered thread configuration was proposed as an alternative geometry for improving the mechanical response of the threaded connection under cyclic loading.

The theoretical stress-concentration analysis and three-dimensional numerical modeling provided the distributions of von Mises stress, fatigue indicator, strain, deformation, and displacement. The obtained results identified the thread root and transition regions as critical locations in the proposed geometry. The numerical results indicate that the tapered geometry provides a gradual variation of the modeled mechanical response along the thread and may contribute to reducing localized stress concentration.

The study provides a numerical basis for further optimization of sucker rod thread geometry. However, the present investigation does not include an experimental validation or a direct quantitative comparison with a conventional thread profile. Therefore, laboratory or full-scale bench testing is required to verify the numerical predictions and to establish the practical fatigue performance of the proposed design.

A quantitative fatigue-life assessment should also be conducted using material-specific S–N data, representative cyclic loading conditions, and appropriate stress ratios. This approach would allow the fatigue performance of the proposed geometry to be expressed in terms of the number of loading cycles and directly compared with conventional thread configurations.

Further development of the present numerical investigation may include experimental fatigue testing and comparative evaluation with conventional thread geometries to further assess the performance of the proposed design under representative operating conditions. In addition, fatigue-life assessment in terms of loading cycles can be developed using material-specific S–N data and representative cyclic loading conditions. The influence of corrosive environments, particularly H₂S- and CO₂-containing fluids, may also be incorporated in future studies to provide a more comprehensive assessment of the threaded connection under downhole operating conditions.

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