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NUMERICAL SIMULATION FOR OPTIMIZING HOLE UTILIZATION IN CRACK REPAIR IN FRETTING FATIGUE

ABSTRACT

This study investigates the stop-hole technique for crack repairs in structural parts subjected to fretting fatigue. The drilling of a hole at the crack tip relieves the concentration of stresses around the crack, which prevents further growth. The maximum von Mises stress is considerably reduced by a stop-hole, as can be seen from the analysis. The configuration with a double stop-hole reduces it to 641 MPa with a 50 µm radius. An exploration of different radii shows that a higher radius value increases stress relief, while the best range is between 60–80 µm. To see exactly how this optimal range improves fatigue life, the number of cycles to crack initiation was computed; the optimal range thus significantly extends the repaired component's lifetime. These findings suggest that stop-hole design optimization may be required to achieve enhanced durability for extending the service life of a fatigued component.

Keywords: *stop-hole technique; crack repair; fretting fatigue; structural integrity*

INTRODUCTION

Cracks in industrial components may cause serious risks to machinery and structure safety, reliability, and performance. The origin of such cracks can be material defects, stress concentrations, corrosion, or fatigue, and if not treated, they can rapidly grow and lead to sudden failures [1,2]. These types of failures have much more serious consequences in critical industries such as aerospace, automotive, manufacturing, and energy production and generally result in costly downtime, damage to equipment, and even injury or loss of life [3,4]. Various crack repair methods have been developed by engineers and researchers; each has certain advantages and limitations. Of these, hole technique and interference fit process have been found quite effective for the retardation in crack growth and the recovery of structural components integrity [1,5–7].

The hole technique is one of the most common techniques, consisting of drilling several small holes along the crack tip. Stress concentrations are basically redistributed by these holes. They alter the distribution of stresses around the crack to decrease the intensity of local stresses at

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the crack tip. By optimal selection of hole dimensions, geometry, and array, crack growth arrest can effectively be achieved for arresting further crack growth in structure damage [8,9]. This technique, again is effective in situations when the orientation of the crack and material properties are known, hence the intervention could be made more precisely. This method, though very effective has its own set of applicability issues, related to geometry of the structure and accessibility of the area where the drilling may not be possible. Interference fit is a method that introduces compressive stresses to counteract crack growth. The procedure consists of inserting a pin or plug in the area of the crack and creates an interference fit that subsequently squeezes the material around it. The compressive stresses that result "close" the crack, which cannot grow any further and increases stability of the component [10]. This process is especially useful during cases where geometries or other operational conditions make the drilling process inconvenient, hence an alternative for repair purposes. Furthermore, the interference fit technique has developed capability to tailor for a specific purpose, by changing the parameters like material of the pin, size, and magnitude of interference, hence versatile for crack repair techniques [11,12]. These methods are found to be effective, yet optimization is still extremely challenging. The dimensions, orientation, and material properties of the crack, combined with operational and environmental conditions, have a very strong influence on whether repair work is successfully accomplished. Besides, accessibility, repair cost, and the extent of the damage are other factors that have to be considered in selecting between the hole technique and interference fit process [1,13]. These variables have to be weighed properly by the engineers in order to decide on the best application for any given situation. This is where numerical simulation becomes a very important tool for the engineers. Numerical simulations provide an in-depth study of crack behavior and the performance of various repair methods by using sophisticated computational models. Such simulations enable the determination of important parameters, such as the stress intensity factors, crack opening displacements, and residual stresses, with great accuracy. These, in turn, enable the engineers to arrive at the best design and application method of the techniques for maximum efficiency and reliability [13,14]. Besides, numerical simulation of the fracture propagation and healing mechanics opens new frontiers to innovative solutions of traditional problems relating to structural integrity.

In the last years, computational methods have been combined with experimental techniques, further enhancing crack repair. Real data is combined with simulated scenarios for the validation of the models and further improvement of the predictions by the engineers; this leads to more reliable results [15]. For instance, FEA has become a cornerstone for the performance of the hole technique and the interference fit process under various conditions. That is to say, these carry with them the benefits of reducing testing time and iterative trials, thus hastening investigations into a better repair strategy [7]. In conclusion, crack repair techniques should be continuously improved through numerical simulation and experimental validation in order to ensure industrial component safety and longevity. Consequently, both innovative repair techniques and state-of-the-art computational methodologies will certainly keep being increasingly relevant because industries ask continuously for higher and more reliable performances. Addressing complex fracture issues and solutions associated with this scenario by a responsible engineer contributes not only to controlling risks but to increasing resilience across various critical infrastructure asset classes.

In this research, an attempt has been made to assess the efficiency of the hole technique process for crack repair by numerical simulation. Emphasis is focused on the number of cycles to the second crack initiation using Fe-safe software, one of the key parameters of crack analysis on crack propagation and repair efficiency. In the paper, different numerical models are investigated in various scenarios in order to provide valuable insights into the parameters affecting crack repair and propose optimized strategies that might enhance the safety and reliability of industrial components. We hope the research will contribute to the development of continued efforts toward advanced crack repair techniques that may assure the continued operation and safety of industrial equipment in every field.

EXPERIMENTAL SETUP

The discussion is qualitative and based on experimental results dealing with the effect of residual stresses around crack tips redistributed by the insertion of pins into holes on direction of crack growth and rate of crack growth. Figure 1 represents a schematically reoriented crack growth which in most drilling methods is expected to retard crack growth.

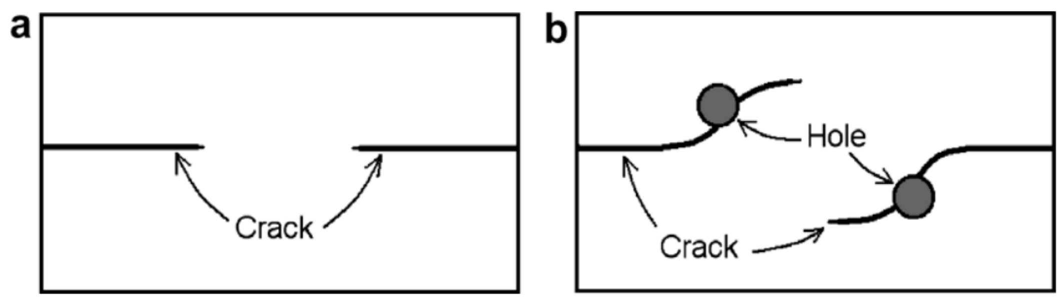

Fig. 1. Anticipated change in crack growth direction caused by drilled holes: (a) in the absence of holes (b) when holes are present [16]

It is also considered one of the fatigue alleviation techniques, as it reduces stress and controls crack growth in structural parts. Engineers can reduce the stress concentration around the crack tip by re-distribution, retard crack growth, and improve fatigue life by applying strategic drilling of holes at specific location and orientation. This technique is of particular value in aerospace and automotive applications where components are under cyclic loading and need to retain high levels of reliability and durability. Experimental investigations will quantitatively establish the effectiveness of hole drilling in reducing stress concentration and controlling crack propagation, thus providing valuable data for structural design optimization with a view to long-term integrity of critical components.

Numerical simulation of hole in cracked specimen

The research focuses on aluminum alloy 2024-T3, a widely used material in the aerospace industry due to its excellent fatigue resistance and corrosion properties. A linear elastic material model was used. Key mechanical characteristics, such as a Young's modulus of 72100 MPa and a Poisson's ratio of 0.3, are noted in references [17,18].

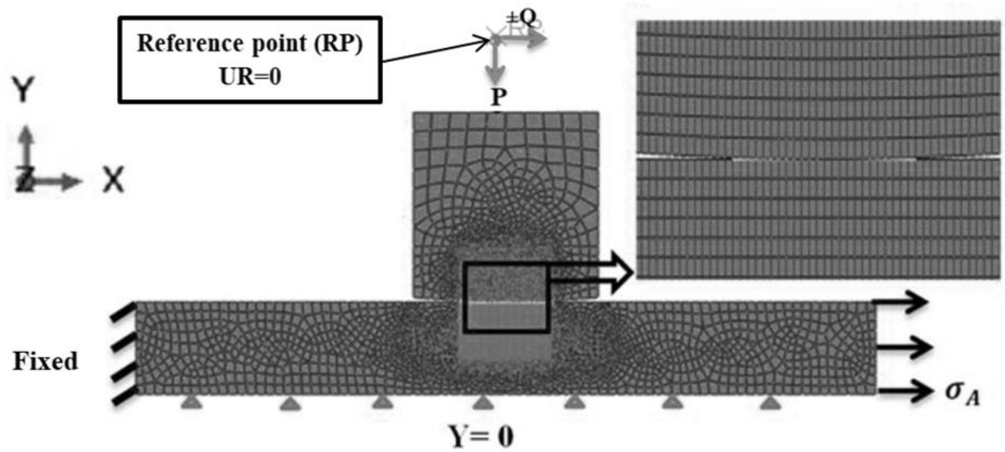

Fig. 2. Illustration of the loading conditions applied in the finite element model [18]

In Abaqus, the contact interaction is modeled using a Master/Slave algorithm, ensuring that the slave surface does not penetrate the master. Two different algorithms are available for handling contact and friction. The friction coefficient between the pad and plate is 0.65. To replicate fretting fatigue conditions accurately, the loading process is divided into three phases: the application of an initial normal load of 543 N, a tangential force Q of 155 N with a frequency of 1 Hz and a load ratio $R_Q=-1$, and an axial stress σ_A=100 MPa with a frequency of 1 Hz and a stress ratio R_σ=0.1. Additionally, the contact zone is subdivided to improve mesh precision, as illustrated in Figure 2. The Finite Element Method (FEM) is applied using Abaqus, with a finer mesh near the crack tip (element size = 5 μm). Mesh details include 13960 nodes, 13881 elements, and a structured mesh topology near the crack tip.

Overall, there is a strong correlation between the analytical and finite element solutions, as illustrated in Figure 3. The analytical solution is represented in formulation (1). The percentage error between the analytical peak shear traction and the finite element results is less than 5%, while the error in semi-contact width remains below 2% across all models. Although there are minor discrepancies when the tangential stress reaches its maximum, the results remain consistent with the analytical predictions. Different regions correspond to distinct physical mechanisms that govern the fretting fatigue process.

$$Q'(x)=\begin{cases}\mu p_0\sqrt{1-(\frac{x}{a})^2} & \text{If} \quad -a\le |x|\le -c+e\\ \mu p_0\sqrt{1-(\frac{x}{a})^2}-\mu p_0\frac{c}{a}\sqrt{1-\left(\frac{x-e}{c}\right)^2} & \text{If} \quad -c+e\le |x|\le c+e\\ \mu p_0\sqrt{1-(\frac{x}{a})^2} & \text{If} \quad c+e\le |x|\le a\end{cases} \tag{1}$$

Q^* represents the maximum applied tangential force, which is 155 N. The coefficient of friction, denoted as μ, is 0.65. The variable x indicates the position, while x/a denotes the normalized position. The parameter a represents half the length of the pad/specimen contact and can be calculated using the following formulation:

$$a = 2(\frac{PR}{\pi E^*})^{1/2} \quad (2)$$

The applied force in the specimen, denoted as P, is 543 N, as shown in Figure 2. The radius of the specimen, represented by R, is 50 mm. The equivalent elastic modulus, denoted as E^*, can be calculated using the following formulation:

$$E^* = (\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2})^{-1} \quad (3)$$

E represents the modulus of elasticity, while ν denotes Poisson's ratio. The maximum pressure distribution at the center of the contact zone, denoted as p_0, can be calculated using the following formula:

$$P_0 = \frac{2P}{\pi a} = (\frac{PE^*}{\pi R})^{1/2} \quad (4)$$

The parameter c represents a threshold distance from the center of the contact zone, indicating the point at which the shear traction distribution transitions. It can be calculated using the following formula:

$$c = a \times \sqrt{1 - \left|\frac{Q^*}{\mu \times P}\right|} \quad (5)$$

The parameter e denotes an offset or shift in position, enabling adjustments to the transition point defined by c. It can be calculated using the following formula:

$$e = \frac{\sigma_A\, a}{4\mu p_0} \quad (6)$$

σ_A represents the fatigue pressure in the specimen, which is 100 MPa, with a fatigue ratio of 0.1, as illustrated in Figure 2.

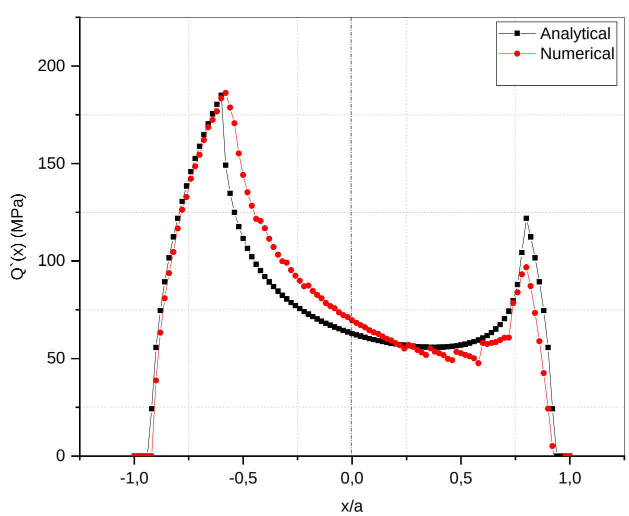

Fig. 3. Validation numerical model

The zone of low shear traction represents the "stick zone," where there is no relative sliding between the surfaces. In contrast, the partial slip zone, where higher shear traction is observed, is where fatigue cracks initiate, and wear particles are generated due to repeated deformation.

Understanding the fretting wear mechanism is practically significant for predicting the service life of contact connections. The shortest lifespan is expected in connections transitioning from partial slip to severe slip, where wear particle formation is rapid, but removal from the contact area is hindered.

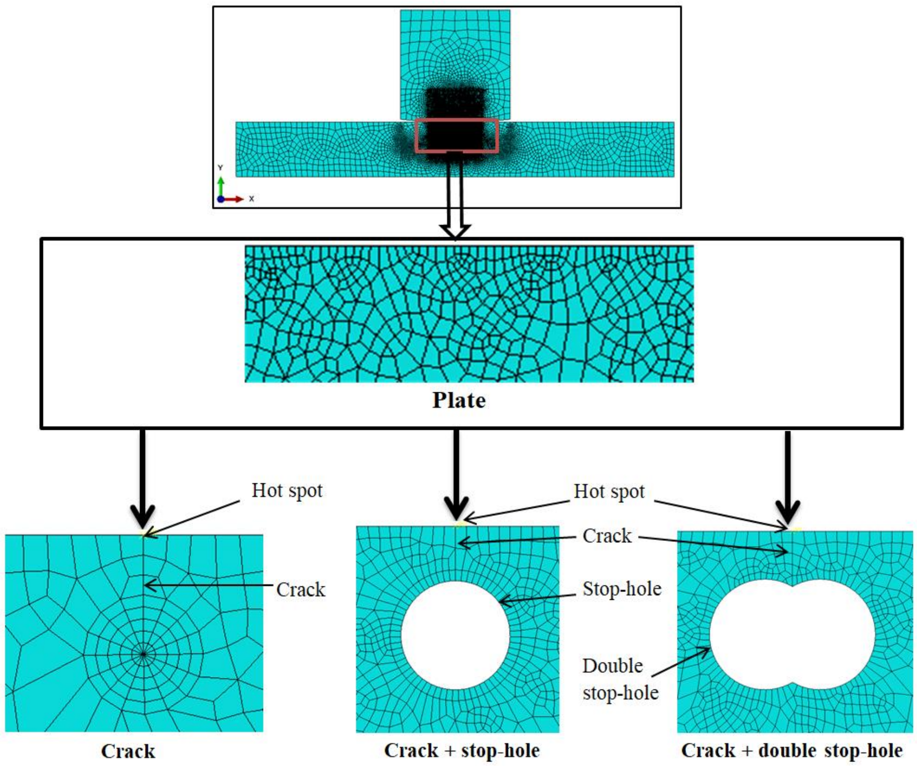

Fig. 4. Geometrical configurations of crack and stop-hole cases

In this study, we investigate the effect of the stop-hole technique on a cracked plate by introducing a 50 µm crack, similar to the method employed by Hojjati-Talemi et al. (2014) [19]. In the first scenario, a 50 µm crack is created in the plate. In the second scenario, a 50 µm crack is combined with a stop-hole of 50 µm radius. Finally, in the third scenario, a 50 µm crack is introduced alongside two stop-holes, each with a radius of 50 µm. The setup for each case is illustrated in Figure 4.

RESULTS AND DISCUSSION

The stop-hole method applies the principles developed for the repair of fatigue cracks, in which the hole drilled at the crack tip stops the propagation by lowering the stress concentration; it does indeed disrupt the crack path and distributes the stress anew. As shown in Figure 5, the introduction of a 50 µm hole on the fretting fatigue plate reduced the maximum von Mises stress from 938 MPa to 719 MPa and hence proved effective. The geometrical change increases the energy necessary for the crack to propagate, while the hole acts as a stress relief, thus improving the load capacity. Work done by [20] shows how these modifications increase fatigue resistance and how stress-relief strategies improve durability under dynamic loading. Further investigators

[21,22] have found that stop-hole repairs can dramatically increase the longevity of components, especially within the aerospace and automotive sectors.

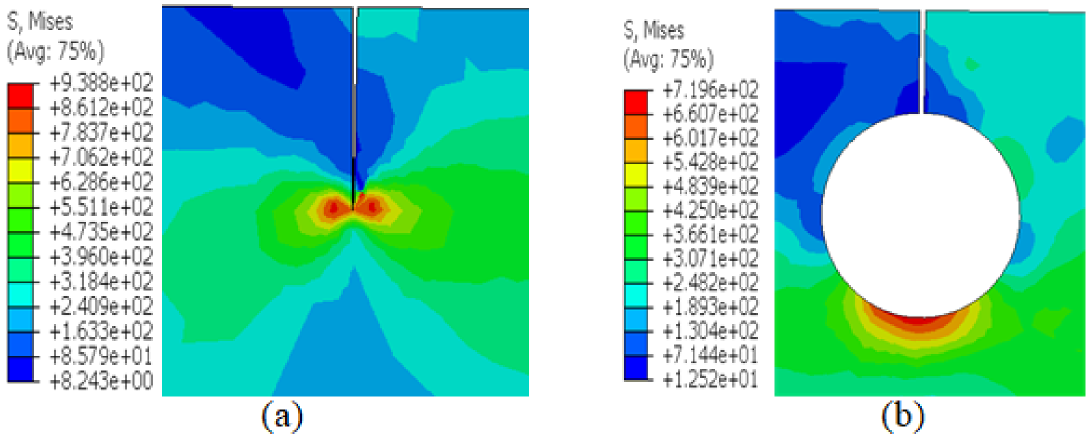

Fig. 5. Von Mises stress distribution in a cracked fretting fatigue plate. a) without hole; b) with 0.05 mm hole

The analysis clearly demonstrates that modifying the stop-hole radius from 50 µm to 100 µm results in a significant reduction in stress levels, as determined using fe-safe software. Specifically, crack initiation life was estimated using fe-safe, which is fully compatible with Abaqus and supports various fatigue life prediction methodologies. We selected the von Mises stress-based approach with an R-ratio SN curve for this study. This method was chosen because it aligns well with the material properties and loading conditions. The choice of methodology directly influences the predicted values, as different methods account for varying fatigue mechanisms and stress-strain relationships. Figure 6 shows that the log-life repeats increase significantly, from 3.62 with the 50 µm stop-hole to 4.41 with the 100 µm stop-hole. This 21% increase in fatigue life underscores the effectiveness of enlarging the stop-hole in alleviating stress concentrations around the crack tip.

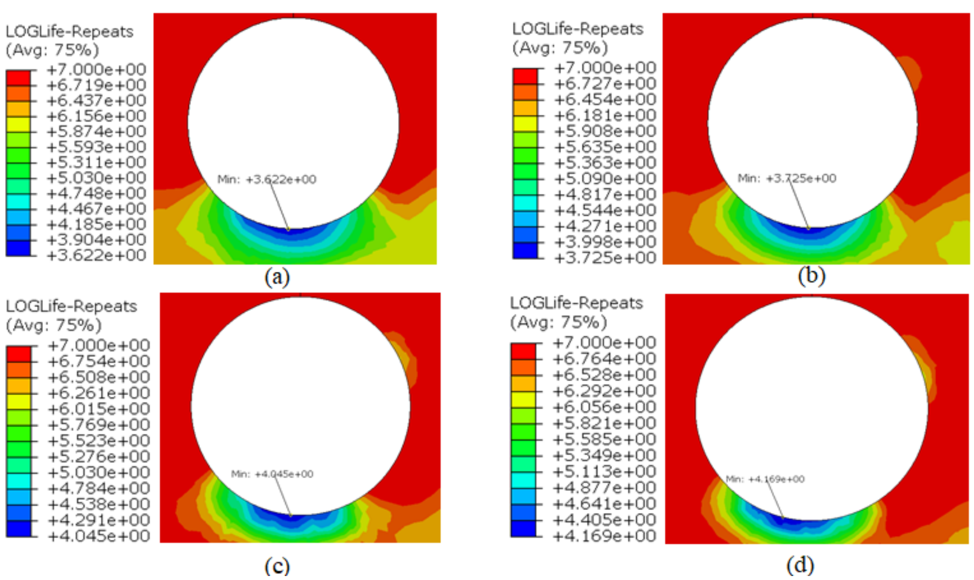

Fig. 6. Log-life repeats in a cracked fretting fatigue plate with a hole; a) Rh=50µm, b) Rh =60 µm, c) Rh =80µm ;d) Rh =100 µm

These findings corroborate earlier research that has also underscored the advantages of larger stop-holes in crack repair. For example, Yi et al. (2020) [23] noted that an increase in stop-hole radius led to a decline in K_I, thus increasing fatigue life in aluminum alloys. Besides, Sanati (2015) stated that a larger stop-hole radius favors the redistribution of stress more efficiently, decreasing the localized stresses and postponing crack re-initiation, in line with the results produced here [24]. While it has been noted that increased hole size extends fatigue life, practical limits must also be noted. For example, according to the idea propounded by [25], a stop-hole of excessively large size might endanger the structural integrity by creating further weaknesses and lowering the ultimate load-carrying capability. Therefore, our findings reaffirm a balanced approach; larger stop-holes can have a greater stress relieve factor and add significantly to fatigue life, provided the overall performance characteristics of the structure are not compromised.

The size of the stop-hole radius (R_h) has a significant effect on fatigue life, whereby the number of cycles is seen to increase dramatically as the hole radius expands. As shown in Figure 7, this raised the fatigue life of 4137 for an Rh size of 50 μm to 14041 cycles for R_h of 100 μm, thus attesting the good effect of a larger stop-hole on the life of the component. This line of reasoning follows the observations made by Deng et al. (2022) [13], who established that larger stop-hole radii help decrease stress raising the propagation of the cracks, thus increasing the fretting fatigue life. Conversely, Hu et al. [26] asserted that, with the extension of stop-hole size, there is more attention to stress distribution, which slows down crack growth and increases resistance to cyclic loading.

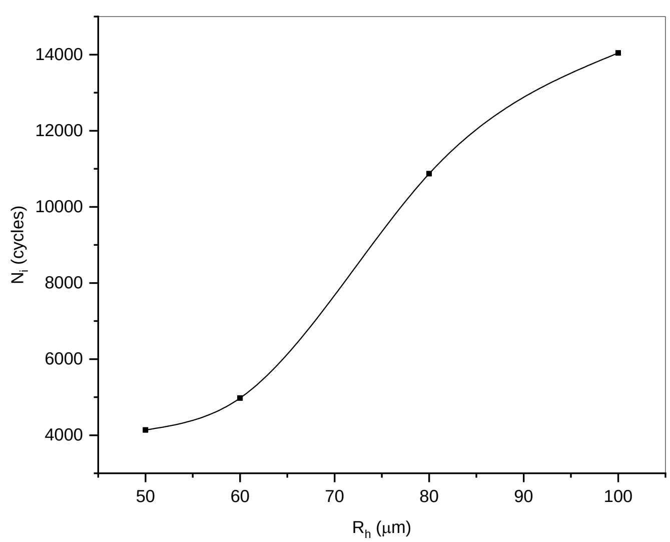

Fig. 7. Number of cycles to the second crack initiation (Ni) as a function of stop-hole radius (Rh)

The substantial increase in the number of cycles with a larger R_h confirms the role of stop-holes in prolonging structural life, as also supported by Fanni et al 2015, who noted that optimizing the stop-hole radius improves fatigue resistance. However, the size of the hole must be carefully selected to avoid undermining the material's overall integrity, as excessively large holes could weaken the structure [27].

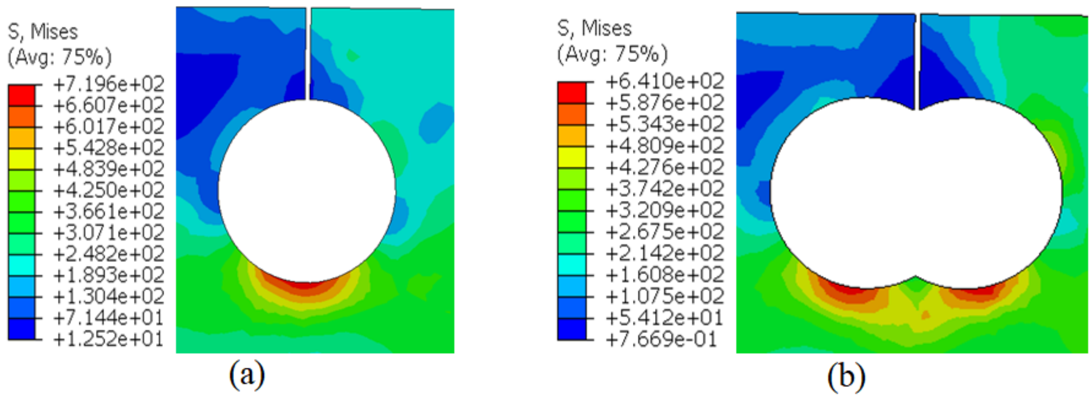

Fig. 8. Von Mises stress distribution in a cracked fretting fatigue plate; a) with a single stop-hole, b) with double stop-holes

Other studies have investigated the double stop-hole technique to evaluate its impact on stress distribution and optimize its application. In this context, a double stop-hole with a radius of 50 µm reduces von Mises stress concentrations from 719 MPa, observed with the standard single stop-hole, to 641 MPa using the double stop-hole configuration, as shown in Figure 8. This reduction demonstrates the efficacy of the double stop-hole technique in mitigating stress concentrations, which is a key factor in extending the lifespan of repaired components.

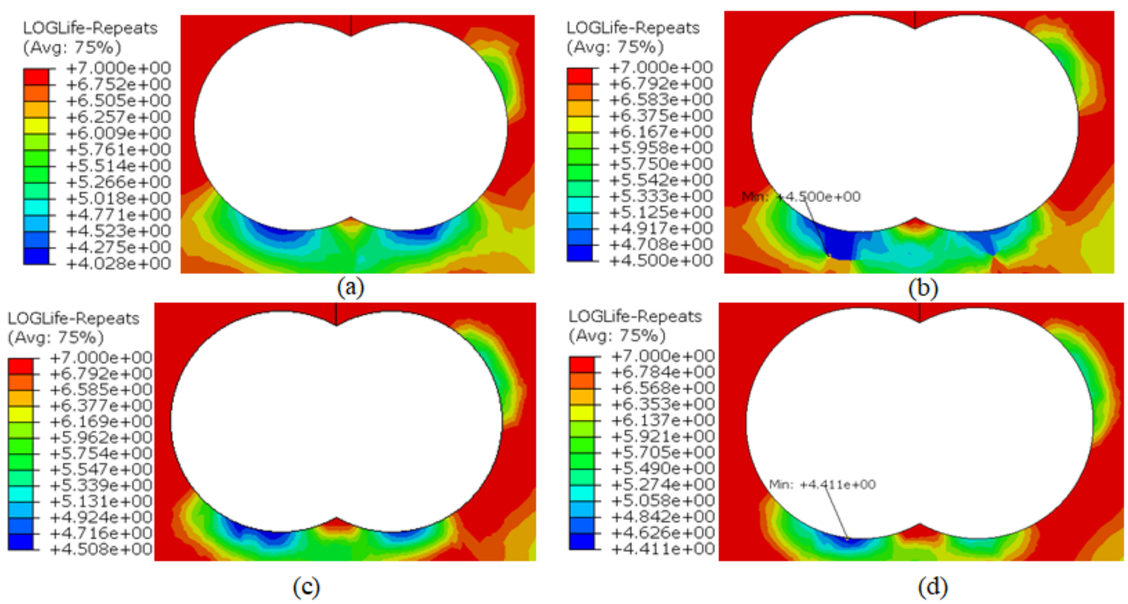

Fig. 9. Log-life repeats in a cracked fretting fatigue plate with double stop-holes; a) Rh=50µm, b) Rh =60 µm, c) Rh =80µm ;d) Rh =100 µm

The contours of log-life repeats for the double stop-hole configuration, shown in Figure 9, indicate that an 80 µm radius achieves the highest log-life value, reaching 4508 cycles. A comparison of the 60 µm and 80 µm radii reveals only a slight difference in fatigue life, suggesting that the 80 µm radius offers an optimal balance between reducing stress and maintaining structural integrity. This observation aligns with Hu et al. (2020) [26], who found minimal fatigue life gains beyond certain stop-hole sizes, reinforcing the significance of selecting an ideal radius for effective stress relief. Overall, these results underscore the effectiveness of the

80 μm radius in maximizing the double stop-hole technique's impact, with further radius increases offering diminishing returns in both stress mitigation and fatigue life extension.

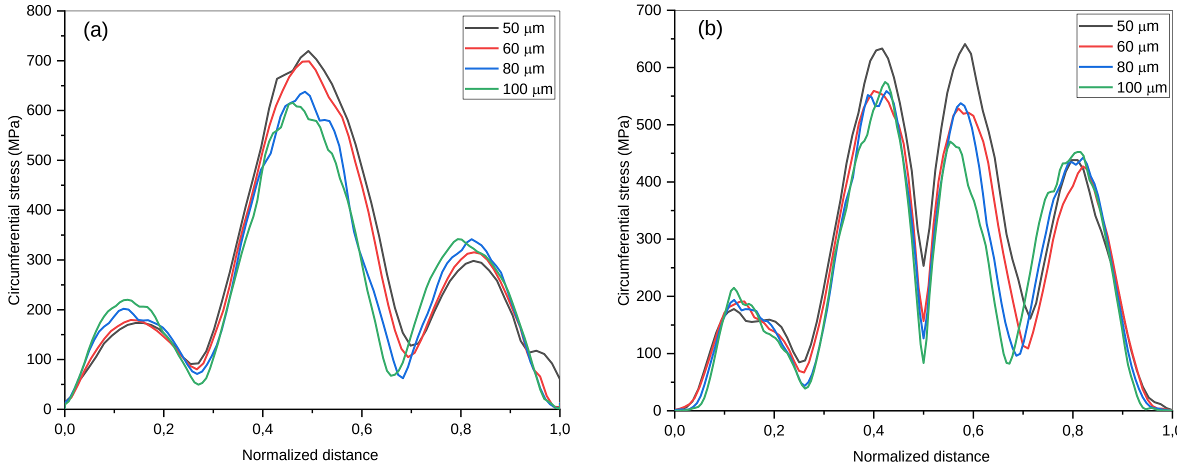

Fig. 10. Circumferential stress distribution along the hole edge for different radii in repaired specimens: a) single stop-hole, b) double stop-hole

The distribution of the circumferential stress along the edge of the hole in repaired specimens varies drastically with radius size, as shown in Figure 10. In this analysis, the relative effectiveness of single-stop-hole and double-stop-hole techniques is compared. A single stop-hole repair, of the smaller radius, e.g., of 50 μm, shows the peak stresses that could reach roughly 730 MPa. As the radius increases, they come down; the 100 μm radius has produced the best stress reduction.

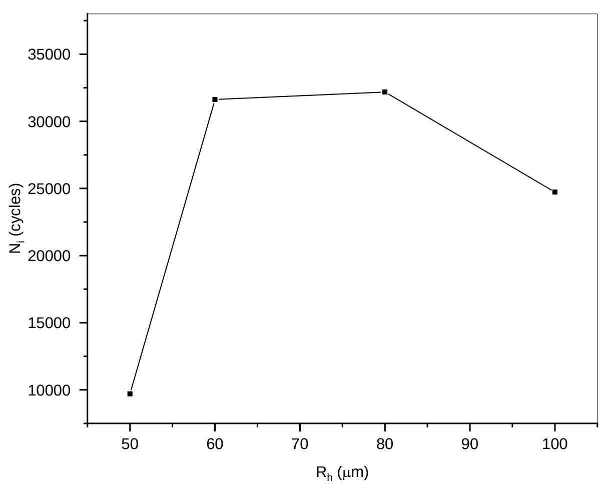

Fig. 11. Number of cycles to the second crack initiation (Ni) as a function of double stop-hole radius (Rh)

This trend shows large radii are favorable to reduced stress concentrations, which can provide resistance to crack initiation and propagation. The excessive enlargement of the radius, however, could diminish structural integrity by removing a considerable amount of material, thus the requirement of an optimized radius selection. Contrary to the single stop-hole configuration, the double stop-hole does, however, have lower peak stresses that are a demonstration of the enhanced capability of relieving stress. The stress distribution in this configuration is also uniform, helping in the better distribution of load, thus improving the fatigue life of the component. The increase in the radius is a gradual reduction in peak stress starting from 50 to 100 µm in double-stop-hole together, where an optimal range for the radius is between 60 µm and 80 µm. This balance between an effective reduction in stress and material retention rationalizes the choice for an appropriate radius and stop-hole configuration. These results signify that improved techniques of repair, when undertaken, will considerably enhance the fatigue life of components subjected to fretting fatigue.

The relationship between the number of cycles and hole radius (R_h), depicted in Figure 11, further supports the findings from Figure 9. The data shows that a double stop-hole with an 80 µm radius achieves the highest cycle count, aligning with the previously observed optimal log-life repeats. The minimal difference in fatigue life between radii of 60 µm and 80 µm also underscores that the 80 µm radius is the most effective choice for maximizing the stop-hole technique's capacity to alleviate stress concentrations and extend component longevity.

CONCLUSIONS

The presented research is performed to show how the stop-hole technique could present a possible solution to reduce the stress concentration on cracked fretting fatigue plates. By this new method, dramatic enhancements could be achieved in the management of the stresses, leading to increasing overall durability and performances of the engineering components under the fatigue process. Some of the key results are highlighted as:

- The stop-holes effectively lower maximum von Mises stress.
- Adoption of a double stop-hole technique reduces the stress to 641 MPa with a 50 µm double hole configuration.
- Increasing the radius of a stop-hole will promote the effect of stress relief, and the optimal radius of a double stop-hole is identified at 80 µm, where the value of stress concentration is 558 MPa.
- It is concluded that the mechanical performance is closely related to the size and configuration of the hole.
- The present study justifies the application of double stop-hole techniques as a viable method for crack repair in engineering applications.
- The insights drawn from this study will contribute to the optimization of stop-hole designs, which are related to improved durability and prolonged service life of critical components.
- Further work will be focused on refining these techniques and additional parameters to enhance the effectiveness of crack repair methods.

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