



RESEARCH ARTICLE

Numerical modeling and parametric optimization of rope cutter design for small fishing ships

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ABSTRACT

Marine debris, particularly fishing ropes and nets, poses significant risks to small fishing vessels by causing propeller entanglement, operational failure, and safety hazards. To mitigate these issues, rope cutters are widely used; however, structural failure due to fatigue, especially at critical geometric regions, remains a concern. This study presents a numerical investigation and optimization of rope cutter design using finite element analysis in ANSYS Workbench. The structural behavior of rotating and stationary blades was analyzed under cutting forces ranging from 1000 N to 4000 N. The results show that both components operate within the elastic regime, with maximum stress values below the material yield strength. However, stress and strain are highly localized at the fillet region of the stationary blade, identifying it as the primary site for crack initiation. A parametric study of fillet radius was conducted to reduce stress concentration. The optimal radius of 19.52 mm was found to minimize maximum stress while maintaining acceptable deformation. The proposed optimization improves structural reliability and fatigue resistance without altering material properties. These findings provide practical design guidelines for enhancing the durability and safety of rope cutters used in small fishing vessels operating in debris-prone marine environments.

1. Introduction

Marine debris, including discarded fishing gear, ropes, and other persistent materials, has emerged as a significant challenge for maritime operations due to its adverse impacts on navigation safety and economic activities [1–3]. This debris originates from various sources, such as accidental loss, intentional disposal of damaged or excess fishing equipment, illegal fishing activities, and the high costs associated with proper onshore waste management [3]. Consequently, coastal waters—where small fishing vessels predominantly operate—are increasingly contaminated with floating and submerged debris.

For small vessels, marine debris presents serious operational hazards. Among these, propeller entanglement is one of the most critical issues, as it can substantially impair vessel maneuverability and stability. Such conditions may lead to navigation failure, collisions, operational delays, and dangerous maintenance procedures, including underwater removal of entangled materials, which poses risks of injury to divers [3]. As a result, propulsion system failures caused by debris entanglement can lead to considerable economic losses and threaten crew safety [2–4].

Numerous incidents involving vessel damage, collisions, and fatalities have been reported in connection with marine debris entanglement [4–7]. The occurrence of such incidents is expected to increase due to the rising number of small vessels in coastal regions, intensified maritime activities, and

competitive fishing practices that contribute to the accumulation of abandoned fishing gear in the marine environment.

To address these challenges, rope cutter devices have been developed and widely implemented as protective solutions. Typically installed on the propeller shaft, a rope cutter is designed to sever foreign objects before they can wrap around the propeller [8]. Conventional rope cutter systems generally consist of a rotating blade attached to the shaft and a stationary blade mounted on the stern tube. These components function together based on a scissorlike mechanism, enabling continuous cutting of debris entering the propeller region.

Previous studies have demonstrated the effectiveness and reliability of rope cutter systems. Lee et al. [7] reported a substantial reduction in accident frequency following rope cutter installation, with the average number of incidents decreasing from 6.15 to 1.34 per year, corresponding to a reduction of more than 78%. In addition, Lee et al. [9] investigated the influence of rope cutters on propeller shaft vibration and found that their impact on the dynamic behavior of the propulsion system is negligible, indicating minimal interference with normal operation. Furthermore, Kim et al. [10] conducted a finite element analysis to evaluate the structural performance of a scissor-type rope cutter, demonstrating that the device effectively prevents shaft rotation caused by rope entanglement and ensures reliable cutting performance under various operating conditions. Recently, Nyongesa et al. performed water flow simulations around the propeller blades

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using ANSYS Fluent to investigate the effect of a rope cutter installed on the ship's propeller shaft on the water flow behind the propeller [11].

Despite these advantages, rope cutters remain susceptible to structural failure, particularly at the fillet region of the fixed blade, where stress concentration can lead to crack initiation and eventual fracture. However, existing studies have primarily focused on overall system performance and global structural behavior, with limited attention given to localized stress distribution in critical geometric regions. In particular, the influence of fillet geometry on stress concentration and structural durability has not been systematically investigated. This gap limits the ability to develop optimized designs that directly address the primary failure mechanisms of rope cutters.

To address these limitations, the present study conducts a focused investigation of stress concentration at the fixed blade fillet region and its dependence on geometric design parameters. The main novelty of this work lies in (i) a systematic parametric analysis of fillet angle using finite element analysis (FEA), (ii) the identification of stress reduction mechanisms associated with geometric modification, and (iii) the development of an optimized design guideline to enhance the structural reliability of rope cutters for small fishing vessels.

The findings of this study provide practical design guidelines for improving the structural durability of rope cutters, thereby reducing the risk of in-service failure in small fishing vessels. By enhancing the reliability of these safety devices, the proposed optimization contributes to safer maritime operations and reduced maintenance costs in debris-prone coastal environments.

2. Methodology

2.1. Geometry and Problem Description

The rope cutter system considered in this study consists of two primary components: a rotating blade mounted on the propeller shaft and a stationary blade fixed to the stern tube. These two components interact through a scissor-like mechanism to cut marine debris before it can entangle the propeller (Figure 1). Field observations and failure records indicate that blade fracture most frequently occurs at the fillet region of the stationary blade due to repeated loading. Therefore, this study focuses on the structural behavior of both rotating and stationary blades, with particular emphasis on stress concentration at the fillet region of the stationary blade. The baseline geometry of the rope cutter was modeled based on the actual design used in practice, where the initial fillet radius of the stationary blade is 14 mm. This configuration is used as the reference case for subsequent optimization.

2.2. Material Properties

The rope cutter components are assumed to be made of structural steel commonly used in marine applications. The material is modeled as homogeneous, isotropic, and linearly elastic. The key mechanical properties used in the simulation include:

- Tensile yield strength: 207 MPa;
- Ultimate tensile strength: 586 MPa.

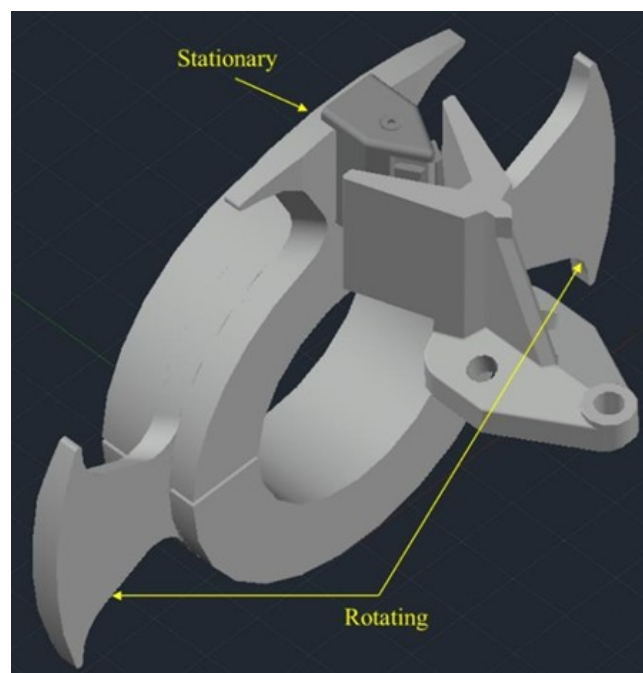


Figure 1. 3D geometry of rope cutter

These values are used to evaluate the structural safety and failure risk under applied loading conditions.

2.3. Finite Element Model Setup

The structural analysis was performed using the Static Structural module in ANSYS Workbench. Three-dimensional (3D) solid models of both rotating and stationary blades were imported into the simulation environment.

2.3.1. Meshing

A finite element mesh was generated using tetrahedral elements. To ensure accuracy in stress prediction, mesh refinement was applied in critical regions, particularly at:

- Blade edges (cutting zone);
- Fillet region of the stationary blade (stress concentration zone).

A finer mesh density was used in these areas to capture stress gradients accurately, while a coarser mesh was applied in non-critical regions to reduce computational cost. A mesh convergence study was conducted to ensure the accuracy of the numerical results. Three mesh densities, including coarse, medium, and fine meshes, were tested by changing the element size and refining the mesh in critical regions, particularly at the fillet and blade edge.

The maximum equivalent stress was used as the convergence criterion. The results showed that when the number of elements exceeded approximately 390,000, the variation in maximum stress was less than 3%, indicating mesh independence. Therefore, the medium mesh, comprising 668,906 nodes and 390,956 elements, provides a good balance between computational efficiency and accuracy. The selected mesh has a maximum Aspect ratio of 7.2, a maximum Skewness quality of 0.7, and a minimum Orthogonal quality of 0.2, ensuring a good quality for CFD simulations. The 3D mesh of the stationary blade of the rope cutter is presented in Figure 2.

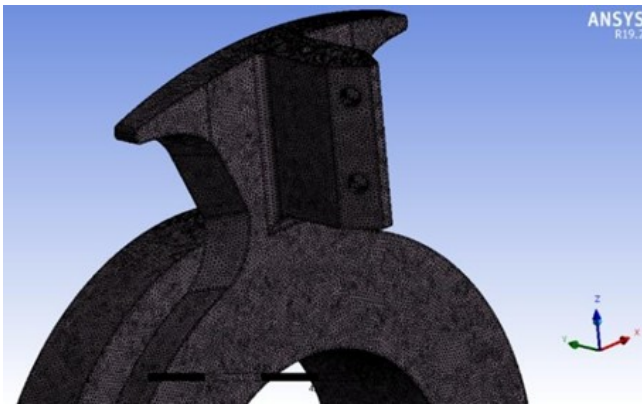


Figure 2. 3D mesh of the stationary blade of the rope cutter

2.3.2. Boundary Conditions

The stationary blade was fixed at its mounting surface, representing its attachment to the stern tube. Meanwhile, the rotating blade was constrained to simulate its connection to the propeller shaft while allowing load transfer at the cutting interface. Cutting forces were applied at the contact region between the rotating and stationary blades, representing the interaction with marine debris during operation.

In the finite element model, the stationary blade was fully fixed at its mounting surface by constraining all translational and rotational degrees of freedom, representing its rigid attachment to the stern tube assembly. The rotating blade was constrained at the shaft connection while maintaining its structural stiffness during load transfer. Instead of explicitly modelling the transient blade-to-rope contact, the cutting action was represented by an equivalent static force applied normal to the cutting edge at the blade–rope contact region, as illustrated in Figure 3. The applied force represents the equivalent cutting resistance generated during rope severing. Frictional contact, plastic deformation of the rope, and progressive material failure were not considered in the present model. Therefore, the analysis provides a conservative elastic structural assessment suitable for evaluating stress concentration and structural integrity under the maximum expected cutting load.

Cutting forces were calculated according to rope diameter and properties. The rope cutter in this study is designed for small fishing ships. Under the working conditions of these small fishing ships, their propellers are often entangled by fishing nets and ropes with diameters ranging from approximately 6 to 14 mm. The theoretical cutting force required to cut a rope is calculated using the following formula:

$$F = \tau A \quad (1)$$

where τ is the shear strength (MPa = N/mm²) and A is the area (mm²).

For marine ropes made of Polypropylene, shear strength (τ) is in the range of 20–35 N/mm².

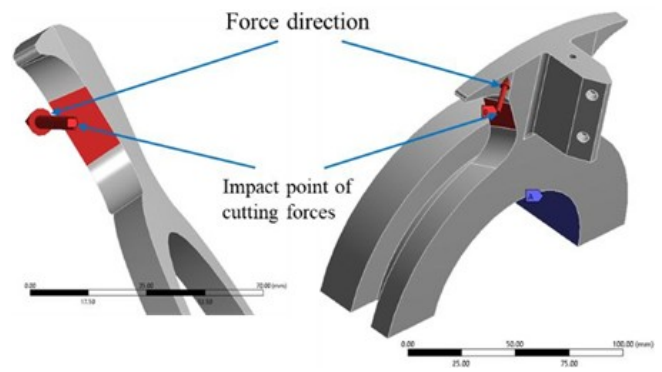


Figure 3. Point of application and direction of the cutting force on rope cutter blades

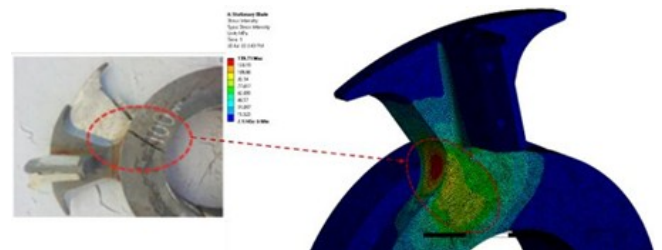


Figure 4. Comparison of the simulation result with the observed fracture locations in real components

The theoretical cutting force is calculated assuming uniform shear failure across the entire cross-section of the rope. However, in practical conditions, the cutting process is highly localized and progressive. The rope consists of twisted fibers that fail sequentially rather than simultaneously. Additionally, stress concentration at the blade edge, combined loading modes (shear, tension, and bending), and the porous structure of the rope significantly reduce the effective resisting area. Consequently, the actual cutting force is typically 50–70% lower than the theoretical prediction [12–15]. This means that to cut Polypropylene ropes with a diameter of 6 mm to 14 mm, the required cutting force will be in the range of 1000 N to 4000 N. In this study, six simulation cases with cutting forces ranging from 1000 N to 4000 N (with increments of 500 N) were performed to evaluate the effect of cutting force, or more precisely, rope diameter, on the stress, strain, and deformation of the rope cutter blades. The force direction was defined according to the actual cutting action, acting at the blade edge where contact with debris occurs. The point of application and direction of the cutting force at the point where the blade contacts the rope are shown in Figure 3.

2.3.3. Structural Analysis

The simulation aimed to evaluate the structural response of the rope cutter under different loading conditions. The following output parameters were obtained:

- Equivalent (von Mises) stress;
- Equivalent elastic strain;
- Total deformation.

The results were analyzed to identify critical stress regions and assess whether the stresses exceed the material yield strength. Particular attention was given to the fillet region of

the stationary blade, where stress concentration is expected to be highest.

It should be emphasized that the present analysis is based on a linear elastic material model and an equivalent static loading condition. Consequently, the computed von Mises stresses should be interpreted as an upper-bound assessment of elastic structural safety rather than a complete representation of the actual cutting process. In practical operation, rope severing involves transient contact, localized plastic deformation, friction, and progressive failure of rope fibers, which require nonlinear contact and material damage models. These effects are beyond the scope of the present study and will be investigated in future work.

The present analysis assumes quasi-static loading to evaluate the structural response of the rope cutter under the maximum expected cutting force. In practical operation, however, the scissor-like cutting mechanism involves short-duration contact and impact during rope severing, which may produce transient stress peaks. Although these dynamic effects are not explicitly considered in the present study, the static analysis provides a suitable first-order assessment for identifying stress concentration regions and evaluating the structural integrity of the rope cutter. A more detailed transient dynamic analysis incorporating contact-impact behavior will be considered in future work.

2.4. Model Validation

To verify the reliability of the numerical model, simulation results were compared with actual failure observations of rope cutters in service. The predicted locations of maximum stress were found to coincide with the observed fracture locations in real components, indicating that the finite element model can accurately capture the structural behavior and failure-prone regions of the device.

Figure 4 shows a comparison of the stress concentration location in the simulation with the actual crack location on the device. It should be noted that the validation in this study is primarily qualitative due to the lack of experimental data for the specific rope cutter configuration. The validation is based on the agreement between predicted stress concentration regions and observed fracture locations in real components. Future work will include strain-gauge measurements and transient loading experiments to provide quantitative validation of the finite element model under representative operating conditions.

In addition to the qualitative comparison of crack locations, the computed stress levels were evaluated against established structural design criteria. The maximum equivalent stress obtained under the highest cutting load was 175.16 MPa, which remains below the material yield strength of 207 MPa, corresponding to approximately 85% of the yield strength. Likewise, the maximum stress in the stationary blade was 139.71 MPa (approximately 67% of the yield strength). These results are consistent with the general engineering practice that structural components subjected to occasional peak loading should remain within the elastic regime to avoid permanent deformation. Therefore, the numerical model not only correctly predicts the observed failure-prone region but also

produces stress levels that are physically reasonable according to standard structural design criteria.

2.5. Effects of cutting force on stress, strain, and deformation of blades

2.5.1. Stress Distribution and Failure-Prone Regions

Figure 5 presents the contour distributions of equivalent (von Mises) stress for both the rotating and stationary blades under the maximum applied cutting force of 4000 N. The results clearly reveal the presence of localized stress concentrations in specific geometric regions of both components. For the rotating blade, the maximum stress is primarily concentrated near the inner curved region adjacent to the blade root, as highlighted in the contour plot. This area corresponds to the transition zone between the blade body and the mounting region, where geometric discontinuity induces stress concentration. The stress distribution gradually decreases away from this region toward the outer blade edge, indicating that the cutting edge itself is not the critical location for structural failure.

In the case of the stationary blade, the highest stress is observed at the fillet region connecting the blade body to its base structure. This region exhibits a pronounced stress concentration, as indicated by the red zone in the contour plot. The fillet geometry creates a sharp change in cross-sectional area, leading to elevated stress levels under loading. This observation is consistent with practical failure cases, where cracks are frequently initiated at the fillet region due to cyclic loading. A comparison between the two components shows that, although the rotating blade experiences higher overall stress values, the stationary blade exhibits more severe localized stress concentration.

This distinction is important, as fatigue failure is strongly influenced by stress concentration rather than global stress magnitude.

Furthermore, the contour distributions validate the accuracy of the numerical model, as the predicted high stress regions correspond well with observed fracture locations in actual rope cutter components. This agreement confirms that the finite element analysis can reliably capture the critical stress patterns governing structural failure. These results highlight that the fillet region of the stationary blade is the most critical location for design improvement. Therefore, reducing stress concentration in this region—through geometric optimization such as increasing the fillet radius—is essential for enhancing the fatigue life and overall reliability of the rope cutter.

2.5.2. Strain Distribution and Deformation Localization

Figure 6 presents the contour distributions of equivalent elastic strain for both the rotating and stationary blades under the maximum applied cutting force of 4000 N. The strain contours provide further insight into the deformation behavior and confirm the locations of critical structural response identified in the stress analysis. For the rotating blade, the maximum strain is concentrated in the inner curved region near the blade root, as indicated by the highlighted zone in the contour plot. This region corresponds to the same location where maximum stress occurs, confirming that deformation is highly localized around the geometric transition area. The

strain magnitude gradually decreases toward the outer blade surface, indicating that most of the deformation energy is absorbed near the root rather than at the cutting edge.

In the stationary blade, the highest strain is observed at the fillet region connecting the blade body to its base. This area exhibits a pronounced concentration of strain, as shown by the red zone in the contour. The localization of strain at the fillet is a direct consequence of geometric discontinuity and stress concentration, which amplify deformation under loading. A comparison between the two components reveals that, although the rotating blade experiences higher global stress and strain levels, the stationary blade shows more severe localization of strain at the fillet region. This behavior is particularly important in the context of fatigue, as localized cyclic strain is a key driver for crack initiation and propagation.

Moreover, the strong correlation between the stress and strain contour patterns confirms the consistency of the linear elastic assumption used in the simulation. The identified high-strain regions coincide with the previously observed high-stress zones, reinforcing the conclusion that the fillet region of the stationary blade is the most critical location for structural improvement. These findings further support the need for geometric optimization of the fillet region, as reducing strain concentration will directly contribute to improving fatigue resistance and extending the service life of the rope cutter.

2.5.3. Deformation Distribution and Structural Response

Figure 7 illustrates the contour distributions of total deformation for both the rotating and stationary blades under the maximum applied cutting force of 4000 N. The deformation contours provide insight into the global stiffness and flexibility characteristics of the rope cutter components. For the rotating blade, the maximum deformation is observed at the outer cutting edge, as highlighted in the contour plot. This region experiences the largest displacement due to its distance from the constraint (shaft connection) and its relatively lower structural stiffness. The deformation gradually decreases toward the blade root, where the structure is more rigidly supported. This behavior is typical of cantilever-like components subjected to external loading.

In contrast, the stationary blade also exhibits maximum deformation at the free end of the blade tip. The deformation magnitude in this region is slightly higher than that of the rotating blade, indicating that the stationary blade is comparatively more flexible under the same loading conditions. The deformation distribution shows a smooth gradient from the fixed mounting region toward the blade tip, reflecting a stable and continuous structural response. Unlike the stress and strain contours, where maximum values are concentrated at geometric discontinuities such as fillets, the deformation contours highlight global structural behavior rather than localized effects. The absence of abrupt deformation gradients suggests that no structural instability or excessive localized bending occurs within the analyzed load range.

From a design perspective, although the deformation values remain relatively small and within acceptable limits, the higher flexibility of the stationary blade may contribute to increased cyclic deformation during operation. Over time, this

can amplify fatigue effects, especially when combined with stress concentration at the fillet region. Overall, the deformation analysis confirms that the rope cutter maintains adequate structural stiffness under operational loads, while also emphasizing the importance of optimizing critical regions to balance strength and flexibility for improved durability.

2.5.4. Effect of Cutting Force on Maximum Stress

Figure 8 presents the variation of maximum equivalent (von Mises) stress in both the rotating and stationary blades under different cutting forces ranging from 1000 N to 4000 N. As expected, the maximum stress increases almost linearly with the applied cutting force for both components.

For the rotating blade, the maximum stress increases from 43.79 MPa at 1000 N to 175.16 MPa at 4000 N. Similarly, for the stationary blade, the stress rises from 34.93 MPa to 139.71 MPa over the same loading range. At all load levels, the rotating blade consistently experiences higher stress than the stationary blade, indicating that it is subjected to more severe loading conditions during the cutting process. Despite this increase, the maximum stress values for both blades remain below the material yield strength of 207 MPa, even at the highest applied load of 4000 N. This indicates that the rope cutter operates within the elastic regime under the considered loading conditions, and immediate failure due to yielding is unlikely.

The results suggest that the rope cutter design possesses sufficient strength to withstand instantaneous cutting forces encountered during operation. However, the relatively high stress levels, particularly in the rotating blade at higher loads (reaching approximately 85% of the yield strength), indicate a potential risk of fatigue failure under repeated loading cycles. This observation is consistent with practical failure cases, where blade fracture does not occur due to a single overload event but rather as a result of cumulative damage caused by cyclic stresses. Therefore, while the current design is structurally safe under static loading, its long-term durability is governed by fatigue behavior.

The identification of increasing stress levels with cutting force highlights the importance of reducing stress concentration in critical regions, particularly at geometric discontinuities such as fillets. Since the stationary blade exhibits lower stress but is known to fail at the fillet region in practice, optimizing its geometric features is essential to improving fatigue life. These findings provide the foundation for the subsequent parametric optimization of the fillet radius, aiming to reduce peak stress and enhance the structural reliability of the rope cutter.

2.5.5. Preliminary Fatigue Assessment

Although the maximum equivalent stresses remain below the material yield strength of 207 MPa under all investigated loading conditions, long-term structural integrity is governed primarily by fatigue rather than static yielding. Rope cutters installed on fishing vessels experience repeated cutting cycles throughout their service life, making cyclic loading the dominant failure mechanism.

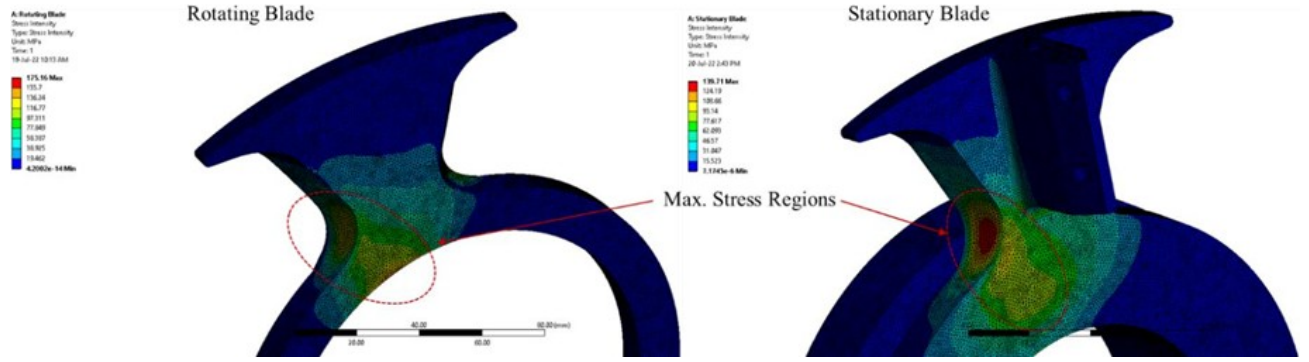


Figure 5. Contour distributions of equivalent (von Mises) stress for both the rotating and stationary blades under the maximum applied cutting force of 4000 N

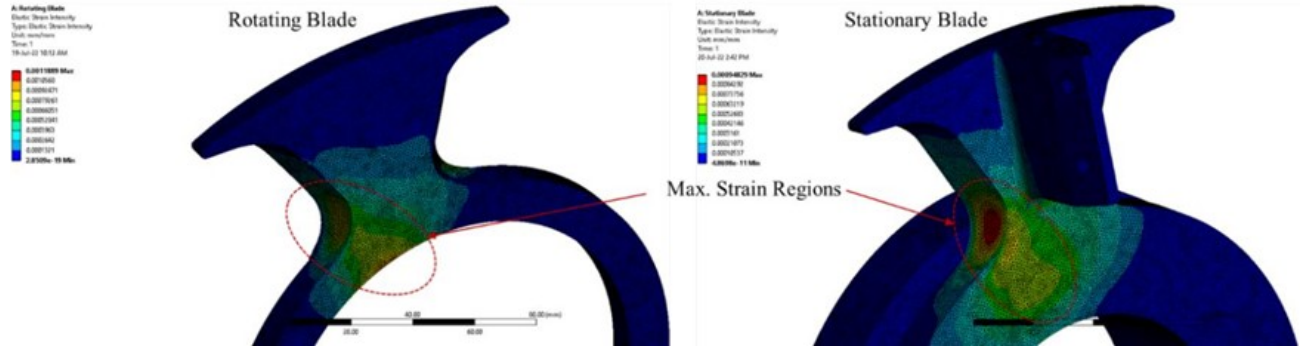


Figure 6. Contour distributions of equivalent elastic strain for both the rotating and stationary blades under the maximum applied cutting force of 4000 N

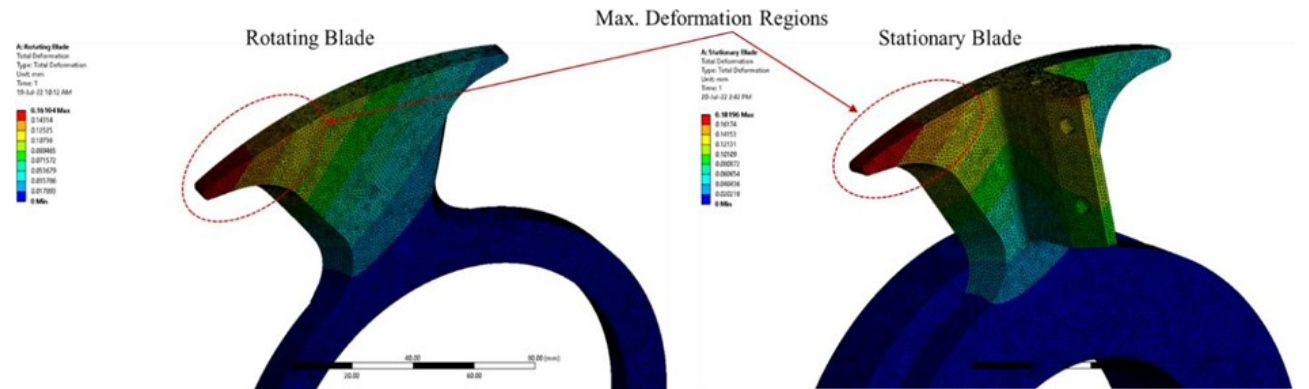


Figure 7. Contour distributions of total deformation for both the rotating and stationary blades under the maximum applied cutting force of 4000 N

A preliminary fatigue assessment was therefore performed using the computed maximum von Mises stresses together with the stress–life (S–N) concept for structural steel. The maximum stress in the rotating blade reaches 175.16 MPa, while the stationary blade experiences a maximum stress of 139.71 MPa under the highest cutting load. Both values are below the material yield strength; however, stress concentration at the stationary blade fillet is expected to reduce the local fatigue strength and promote crack initiation under repeated loading.

According to the S–N behaviour of structural steel, fatigue life decreases rapidly with increasing stress amplitude. Therefore, reducing the maximum stress at the fillet through geometric optimization is expected to improve the fatigue resis-

tance and extend the service life of the rope cutter.

It should be noted that a complete fatigue-life prediction requires additional information, including the loading spectrum, stress ratio, operating frequency, weld quality, surface finish, and environmental conditions. Since these data are unavailable for the present application, only a preliminary fatigue assessment is provided, while comprehensive fatigue-life analysis will be addressed in future work.

2.5.6. Effect of Cutting Force on Maximum Strain

Figure 9 illustrates the variation of maximum equivalent strain in the rotating and stationary blades under cutting forces ranging from 1000 N to 4000 N. Similar to the stress results, the maximum strain in both components increases pro-

gressively with the applied load, indicating a consistent elastic deformation behavior.

For the rotating blade, the maximum strain increases from 2.97×10^{-4} at 1000 N to 1.19×10^{-3} at 4000 N. In comparison, the stationary blade exhibits lower strain values, increasing from 2.37×10^{-4} to 9.48×10^{-4} over the same loading range. This trend is consistent with the stress distribution results, where the rotating blade experiences higher mechanical loading and, consequently, greater deformation. The nearly linear relationship between strain and applied force confirms that both components operate within the elastic regime, as assumed in the numerical model. No abrupt changes or nonlinear responses are observed, indicating the absence of plastic deformation under the considered loading conditions.

The higher strain levels observed in the rotating blade suggest that it is more susceptible to deformation during operation. However, the magnitude of strain remains relatively small, indicating that the structural stiffness of both blades is sufficient to maintain functional integrity during cutting. From a design perspective, although the strain values are within acceptable limits, the accumulation of cyclic strain under repeated loading may contribute to fatigue damage over time. Therefore, reducing localized strain concentrations—particularly in critical regions such as the fillet of the stationary blade—is essential for improving the long-term durability of the rope cutter.

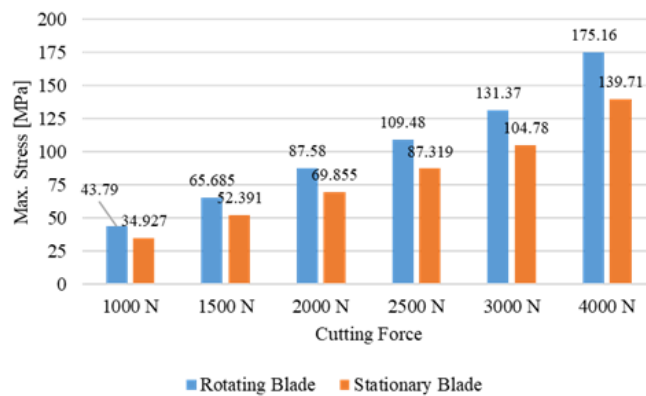


Figure 8. Variation of maximum equivalent (von Mises) stress in both the rotating and stationary blades under different cutting forces

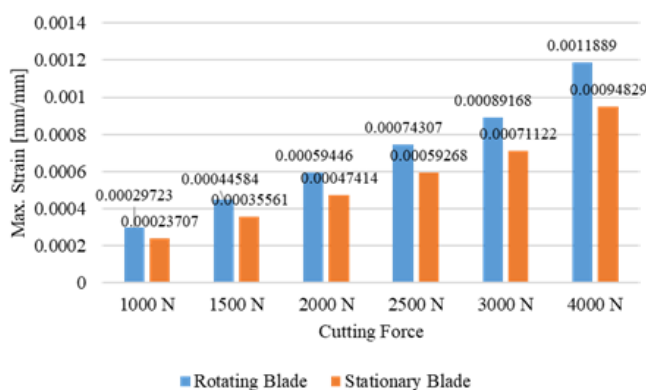


Figure 9. Variation of maximum equivalent strain in the rotating and stationary blades under cutting forces

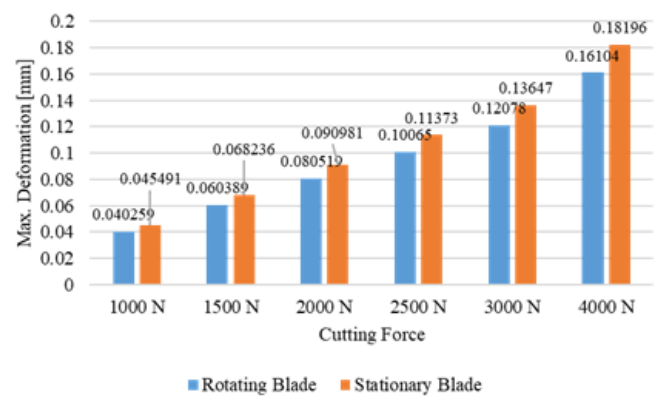


Figure 10. Variation of maximum total deformation for both the rotating and stationary blades under cutting forces

Table 1. Fillet radii of the stationary blade used for simulations

Radius ID	1	2	3	4	5	6	7
Radius [mm]	14	14.72	15.92	17.47	19.52	22.3	28.94

2.5.7. Effect of Cutting Force on Total Deformation

Figure 10 shows the variation of maximum total deformation for both the rotating and stationary blades under cutting forces ranging from 1000 N to 4000 N. As expected, the deformation of both components increases steadily with increasing load, indicating a consistent elastic structural response.

For the rotating blade, the maximum deformation increases from 0.0403 mm at 1000 N to 0.1610 mm at 4000 N. In contrast, the stationary blade exhibits slightly higher deformation values, increasing from 0.0455 mm to 0.1820 mm over the same loading range. This indicates that, although the stationary blade experiences lower stress and strain compared to the rotating blade, it is relatively more flexible under loading conditions. The nearly linear relationship between deformation and applied force further confirms that the system operates within the elastic regime, consistent with the stress and strain results presented earlier. No nonlinear deformation behavior or structural instability is observed within the investigated load range.

The deformation results provide additional insight into the mechanical behavior of the rope cutter system. The higher deformation observed in the stationary blade suggests that it may be more sensitive to geometric modifications, particularly in regions with stress concentration, such as the fillet. This supports the hypothesis that optimizing the fillet geometry can significantly influence both stress distribution and overall structural performance. Although the magnitude of deformation remains relatively small and does not directly compromise functionality, repeated deformation under cyclic loading conditions may contribute to fatigue damage over time. Therefore, minimizing deformation—along with reducing stress concentration—is essential for enhancing the long-term durability of the rope cutter.

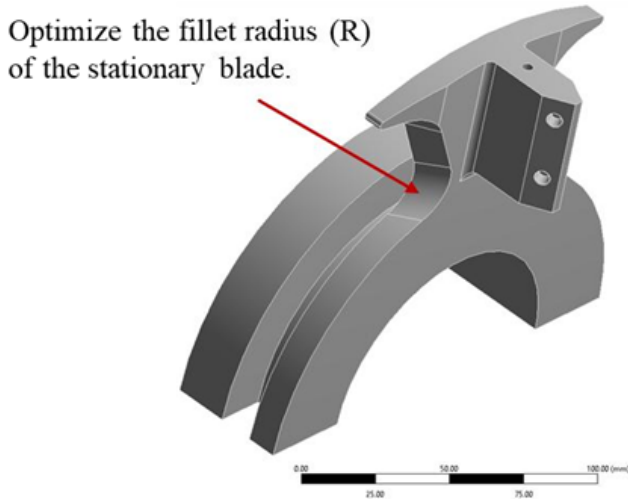


Figure 11. Optimizing the fillet radius of the stationary blade to improve the structural performance of the rope cutter

3. Parametric Optimization of Rope Cutter

3.1. Fillet Radius Optimization Strategy

To improve the structural performance of the rope cutter, a parametric study was conducted on the fillet radius of the stationary blade. Seven different fillet radii were investigated. Table 1 summarizes the simulation cases corresponding to different fillet diameters. For each configuration, the same loading and boundary conditions were applied. The resulting stress, strain, and deformation were compared to evaluate the influence of fillet geometry on structural performance.

In the present study, the fillet radius of the stationary blade is treated as the design variable for structural optimization. The optimization objective is to minimize the maximum equivalent (von Mises) stress in the fillet region, where fatigue cracks are most likely to initiate. During the optimization process, the overall blade geometry, material properties, and loading conditions are kept unchanged, while the total deformation is required to remain within acceptable limits. A systematic parametric evaluation of seven fillet radii is performed to identify the configuration that best satisfies these engineering requirements. Figure 11 illustrates the fillet radius considered in the optimization.

3.2. Evaluation Criteria

The performance of each design was assessed using the following criteria:

- Maximum equivalent stress (primary criterion): Lower stress indicates reduced risk of fatigue failure.
- Strain distribution: Used to evaluate material deformation behavior.
- Total deformation: Ensures that structural stiffness remains within acceptable limits.

The optimal fillet radius was selected as the configuration that provides the best balance between stress reduction and structural integrity.

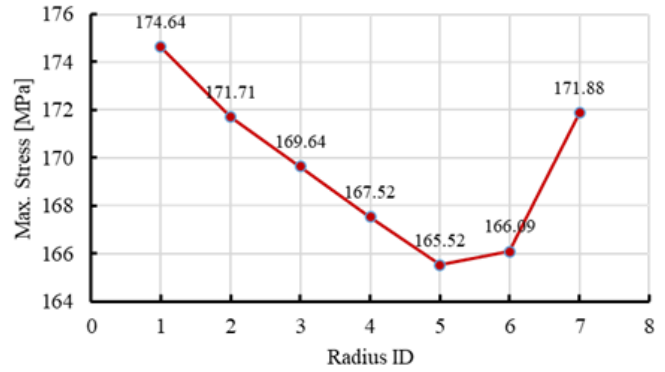


Figure 12. Effect of fillet radius on structural performance

3.3. Optimization Result

3.3.1. Effect of Fillet Radius on Structural Performance

A parametric study was conducted to investigate the influence of fillet radius on the structural behavior of the stationary blade. Seven different fillet radii, ranging from 14 mm (baseline) to 28.94 mm, were analyzed under identical loading and boundary conditions. The results were evaluated in terms of maximum equivalent stress, maximum strain, and total deformation.

As shown in Figure 12, increasing the fillet radius generally leads to a reduction in stress concentration. The maximum stress decreases from 174.64 MPa ($R = 14$ mm) to a minimum value of 165.52 MPa ($R = 19.52$ mm, Radius ID 5). This corresponds to a reduction of approximately 5.2%, indicating that a moderate increase in fillet radius effectively alleviates stress concentration at the critical region.

However, further increasing the fillet radius beyond this optimal value results in a slight increase in stress. For instance, the maximum stress rises again to 171.88 MPa at $R = 28.94$ mm, suggesting that excessive geometric modification may adversely affect load distribution and structural stiffness.

3.3.2. Strain Behavior

Figure 13 shows the effect of fillet radius on structural strain. A similar trend is observed for the maximum strain. The strain decreases from 1.185×10^{-3} ($R = 14$ mm) to a minimum of 1.076×10^{-3} at $R = 19.52$ mm, indicating improved deformation resistance. Beyond this point, the strain begins to increase again, confirming that there exists an optimal geometric configuration that minimizes deformation localization.

3.3.3. Deformation Characteristics

Figure 14 shows the effect of fillet radius on structural deformation. The total deformation results further support the existence of an optimal fillet radius. The deformation decreases progressively from 0.227 mm ($R = 14$ mm) to a minimum of 0.210 mm at $R = 22.3$ mm (Radius ID 6). Although the minimum deformation occurs at a slightly larger radius than that for minimum stress, the difference is relatively small. This indicates a trade-off between stiffness and stress concentration:

- Smaller radii lead to higher stress concentration;
- Larger radii lead to increased flexibility.

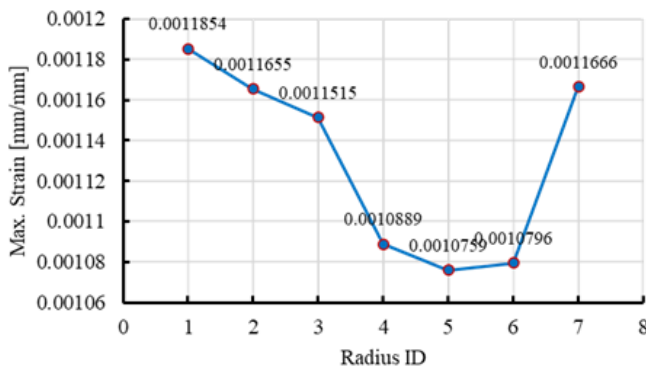


Figure 13. Effect of fillet radius on structural strain

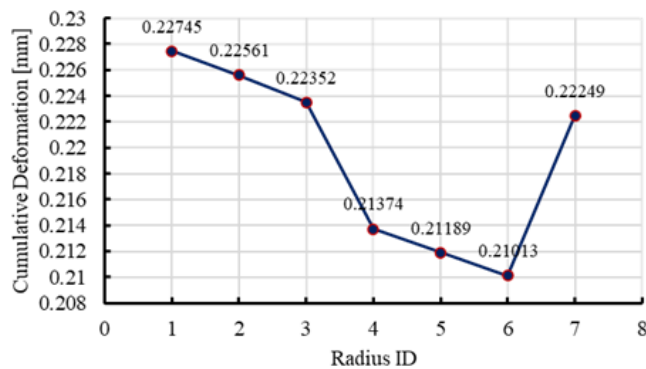


Figure 14. Effect of fillet radius on structural deformation

3.3.4. Optimal Design Selection

Considering all three performance indicators—stress, strain, and deformation—the fillet radius of 19.52 mm (Radius ID 5) is identified as the optimal design. This configuration provides:

- The lowest maximum stress;
- Near-minimum strain;
- Acceptable deformation within structural limits.

Importantly, minimizing stress is the primary objective, as it directly governs fatigue crack initiation and structural failure. Therefore, Radius ID 5 offers the best balance between strength and durability. The results demonstrate that fillet geometry plays a critical role in controlling stress concentration and structural performance. A properly optimized fillet radius can significantly enhance the fatigue resistance of the rope cutter without requiring changes in material or overall design. From a practical perspective, the optimized design:

- Reduces the likelihood of crack initiation at the fillet region;
- Improves service life under cyclic loading;
- Enhances the reliability of rope cutters in debris prone marine environments.

The optimal fillet radius of 19.52 mm reduces stress concentration while maintaining structural stiffness, making it the most effective configuration for improving the durability of rope cutters.

Beyond identifying the optimal fillet radius, the present

parametric study also generates a structured dataset relating geometric parameters to the corresponding structural responses, including maximum stress, strain, and deformation. Although only seven design configurations were investigated, this dataset represents a foundational training matrix that can be expanded in future studies for data-driven design optimization. By increasing the number of geometric variables and sampling points, the finite element results may be employed to develop surrogate models, such as response surface models (RSM), Gaussian Process Regression (GPR), or shallow Artificial Neural Networks (ANNs), capable of rapidly predicting structural performance without performing computationally expensive finite element analyses for every new design. Such surrogate models could significantly accelerate optimization and facilitate intelligent design of rope cutter systems for various vessel sizes and operating conditions.

It should be noted that the present study adopts a parametric approach rather than a formal mathematical optimization framework. The optimal fillet radius is determined by engineering criteria, including minimizing maximum stress and ensuring acceptable deformation. A rigorous optimization formulation would require defining an objective function (e.g., fatigue life maximization or stress minimization) and constraints related to deformation limits and manufacturability. Such an approach is considered a direction for future work.

4. Conclusions and Discussions

This study investigated the structural behavior and optimization of rope cutters for small fishing vessels using finite element analysis. The results provide important insights into stress distribution, deformation characteristics, and failure mechanisms, as well as practical design improvements. The numerical analysis revealed that both rotating and stationary blades operate within the elastic regime under cutting forces ranging from 1000 N to 4000 N. The maximum stress values remain below the material yield strength of 207 MPa, indicating that immediate failure due to static overloading is unlikely. However, relatively high stress levels—particularly in the rotating blade—suggest that fatigue failure under cyclic loading is the dominant failure mechanism in practical applications.

The contour analysis demonstrated that stress and strain are highly localized at geometric discontinuities. In particular, the fillet region of the stationary blade was identified as the most critical location for crack initiation due to severe stress concentration. This finding is consistent with observed failure patterns in real rope cutter components, confirming the reliability of the numerical model. The parametric optimization of the fillet radius showed that geometric modification significantly influences structural performance. Increasing the fillet radius effectively reduces stress concentration up to an optimal value, beyond which the benefits diminish. Among the investigated configurations, a fillet radius of 19.52 mm was identified as the optimal design, achieving the lowest maximum stress while maintaining acceptable strain and deformation levels.

The parametric database established in this work also provides a useful foundation for future intelligent engineering

applications. By combining additional geometric parameters with finite element simulations, the generated dataset may be used to train surrogate models or machine-learning algorithms for rapid structural optimization and real-time design assessment. Such approaches have the potential to significantly reduce computational cost while enabling efficient exploration of larger design spaces.

The preliminary fatigue assessment further indicates that, although the computed stresses remain below the material yield strength, cyclic loading is expected to govern the long-term structural durability of the rope cutter. Consequently, reducing stress concentration at the stationary blade fillet is expected to improve fatigue resistance and extend service life. A comprehensive fatigue-life prediction based on measured loading histories will be investigated in future work.

The results also highlight a trade-off between stress reduction and structural stiffness. While larger fillet radii reduce stress concentration, they may increase deformation and reduce stiffness. Therefore, an optimal balance between strength and flexibility is essential for improving fatigue resistance and overall durability. From an engineering perspective, the proposed optimization provides a practical and cost-effective solution for enhancing the reliability of rope cutters without requiring changes in material or major design modifications. The improved design reduces the likelihood of crack initiation at critical regions, extends service life under cyclic loading, and contributes to safer and more efficient operation of small fishing vessels in debris-prone environments.

Although the current study identifies an optimal fillet radius based on stress and deformation criteria, future work should focus on developing a comprehensive optimization framework incorporating fatigue life prediction and material-dependent behavior to determine a globally optimal design. In addition, future work should also focus on experimental validation and dynamic loading conditions to further improve the accuracy and applicability of the proposed design methodology.

Finally, although the present study focuses on deterministic finite element analysis, the generated stress, strain, and deformation datasets may serve as valuable training data for future structural health monitoring (SHM), predictive maintenance, and digital twin applications. Such datasets could be integrated with operational sensor measurements to estimate remaining useful life and support condition-based maintenance of rope cutter systems.

Author contributions

Van Chien Pham: Methodology, Data management, Investigation, Validation, Grant acquisition, Feedback on peer review, Writing – original manuscript. Duy Nam Ngo: Data compilation, Data analysis, Investigation, Writing – original manuscript. Duy Trinh Nguyen: Supervision, Grant Acquisition, Manuscript Editing. Van Hoan Cao: Supervision, Grant Acquisition, Manuscript Editing. Duy Tan Nguyen: Supervision, Grant Acquisition, Manuscript Editing.

Declaration of competing interest

The authors declare the absence of any potential conflicts of interest from this study and affirm that the paper has not been previously published.

Data availability

Data will be provided upon request.

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