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STRESS AND FATIGUE SIMULATION OF STRUCTURAL BLADES IN MECHANICAL CLEARING OPERATIONS

Florin-Bogdan MARIN[1,2], Iulian CONSTANTIN[1], Mihaela MARIN[1,2]
[1] “Dunarea de Jos” University of Galati, Romania
[2] Interdisciplinary Research Centre in the Field of Eco-Nano Technology and Advance Materials CC-ITI,
Faculty of Engineering, “Dunarea de Jos” University of Galati, Romania, 47 Domnească Street, RO-800008,
Galaţi, Romania
e-mail: flmarin@ugal.ro

ABSTRACT

This study presents a numerical investigation into the structural performance of the cutting blades used in vegetation-clearing operations, particularly within mechanical systems designed for demining or land maintenance. Using finite element analysis (FEA), the research evaluates stress distribution, fatigue behavior, and failure risk under cyclic loading conditions. Multiple simulation models were developed to replicate realistic operational forces and identify critical stress concentration zones. The fatigue simulations provided insights into lifetime predictions and cumulative damage evolution, expressed through percentage-based degradation maps. Von Mises stress analyses further validated the structural response of the blades under high-load scenarios. The results indicate that proper geometric configuration and material selection are essential for improving fatigue life and ensuring operational safety in harsh environments. The proposed methodology supports optimization efforts in blade design for enhanced durability and reliability.

KEYWORDS: structural blades, fatigue simulation, von Mises stress, vegetation-clearing systems

1. Introduction

Mechanical clearing operations - particularly those associated with demining, forestry, or land reclamation - require cutting blades with high structural integrity and fatigue resistance under cyclic and impact loading. These components are repeatedly exposed to dynamic stresses, leading to gradual degradation and potential failure. In such contexts, finite element analysis (FEA) has proven essential for investigating localized stress distributions, fatigue damage evolution, and mechanical lifespan predictions [1-4].

Recent studies in the field of wind-turbine and engine blade analysis offer valuable analogies for vegetation-clearing blades, as both exhibit similar fatigue mechanisms and stress localization challenges. For example, Halley *et al.* employed submodeling techniques to analyse fatigue in turbine blade trailing edges, identifying critical high-cycle failure zones [1]. Fatigue behavior modeling under repeated mechanical loading has further revealed the significance of geometric concentration zones in stress accumulation [2]. García-Márquez and Arellano-Carbonell demonstrated how cumulative damage can be estimated using fatigue mechanics, guiding structural reinforcements in blade-like geometries [3].

From an engineering failure standpoint, Perez and Lee reviewed various detection techniques for fatigue-induced degradation, emphasizing the importance of predictive modeling in dynamic components [4]. In high-load rotating systems, such as wind turbines or demining blades, fatigue life prediction based on multiaxial S-N curves becomes essential [5]. These methods have been expanded by researchers like Ramezani and Jafari, who proposed reliability-based frameworks for fatigue assessment in composite and metallic blades [6].

Failures in mechanical blades are also influenced by operational and manufacturing variability. Notably, Nelson et al. investigated real-world fatigue fractures in CFM56-engine fan blades, showing how microstructural and cyclic effects accelerate damage [7]. In mechanical joints, fretting fatigue remains a critical failure mechanism, reducing fatigue thresholds in components under vibrational stress, as reviewed by Mirhosseini and Panahi [8]. In wind turbines, Oliveira and Ribeiro explored root causes of failure in composite blades, identifying delamination and stress concentrations as key triggers [9].

Shen and Wang investigated reinforced blade behavior under fatigue bending, aligning closely with the requirements of structural blades in vegetation-clearing machines [10]. Thermal loading effects in such components have also been assessed, as shown in Liu and Zhang's study of engine blades [11]. Computational models developed by Carreon and Ramos have proven that 3D simulation techniques can accurately replicate stress propagation in flexible blade structures [12].

Beyond fatigue, static bending and structural reinforcement using graphene and hybrid materials have gained traction. Studies by Eslami and Saadatnia, and Bian and Han, evaluated how nanoscale reinforcement can significantly enhance mechanical response and fatigue life in composite blades [13, 14]. Moreover, structural optimization through refined blade tip geometry has been shown to reduce stress peaks and delay fatigue failure [15].

Advanced material integration, such as graphene platelet-reinforced composites, has been examined by Kang and Ahn for thermal fatigue resistance in rotating systems [16]. Xu and Ma further analysed crack propagation in nanostructured blades using static and fatigue-based FEM [17]. Comparative studies by Patel and Lee concluded that accurate fatigue prediction in solid FE models is crucial for operational safety [18].

Horvat and Mišković modeled mistuned blade behavior in turbines, revealing failure acceleration due to vibrational mismatches [19], while Kumar and Rai simulated diametrical blade compression to estimate fatigue thresholds [20]. Finally, Filip and Golea applied FEM to simulate critical loads in composite blades, providing a robust method for predicting failure onset [21].

Despite the extensive research on turbine and engine blades, limited work exists on cutting blades for vegetation-clearing systems. The present study addresses that gap by conducting a comparative FEM-based fatigue analysis of two blade variants - one metallic and one polymeric - under identical boundary conditions. The aim is to evaluate stress concentration zones, von Mises distributions, damage percentage evolution, and structural durability in real-world scenarios. The findings contribute to design optimization for cutting systems in harsh environments where cyclic mechanical stress governs reliability and safety.

2. Experimental Procedure

The experimental methodology in this study is entirely based on numerical simulations using finite element analysis (FEA), aimed at evaluating the structural behavior and fatigue performance of cutting blade components used in mechanical vegetation-clearing operations. Two blade variants were investigated: one made from structural steel and the other from a high-strength polymer. Both were designed to replicate a realistic blade geometry commonly used in modular cutting systems.

The modeling phase involved the three-dimensional geometric design of the blade assemblies, followed by their transfer to a simulation environment for meshing and structural analysis. The mesh structure was refined using a tetrahedral configuration, with higher density around stress concentration zones, such as sharp transitions, bolt holes, and the blade tip. Mesh convergence analysis ensured the accuracy of the results and numerical stability. The boundary conditions were applied uniformly across both models to allow for a comparative assessment. A fixed-support constraint was imposed at the mounting base, simulating the bolted connection to the cutting drum or support shaft. A distributed pressure load was applied along the cutting edge, mimicking operational contact forces with dense vegetation or surface material. In addition, gravity was considered to replicate self-weight effects under dynamic loading.

The material properties were assigned based on standardized engineering datasets. The structural steel model included isotropic elasticity, yield strength, and fatigue limit data derived from the EN S235JR specifications. The polymer variant was modeled using nonlinear elastic-plastic behavior with viscoelastic considerations, appropriate for high-density polyethylene (HDPE) or reinforced composites. The fatigue simulations were performed under fully reversed cyclic loading conditions ($R = -1$), using a stress-life (S-N) approach calibrated for high-cycle fatigue regimes. The simulations focused on identifying regions of stress concentration, cumulative damage, and fatigue life prediction using the Goodman mean-stress correction model. Damage-evolution maps and safety-factor contours were generated to visualize component degradation over time.

For von Mises stress analysis, linear static simulations were conducted to identify the peak-stress zones under maximum applied loads. These results were then cross-referenced with fatigue damage outputs to assess structural risk over time. Comparative evaluations were made based on maximum equivalent stress, total deformation, fatigue life (in cycles), and damage percentage. All simulations were performed at room temperature, and material behavior was assumed to be homogeneous and isotropic unless otherwise specified. The methodology ensures repeatability and relevance to real-world operating scenarios while also supporting future optimization efforts for blade design and material selection.

3. Results and Discussion

The simulation results highlight the structural and fatigue behavior of the two analysed cutting blade variants under identical mechanical loading conditions. The comparison was based on key performance indicators such as von Mises stress distribution, total deformation, fatigue life, and cumulative damage. Figure 1 shows the fatigue stress distribution across the blade under repeated mechanical loading. High-risk zones are highlighted, providing insight into potential failure initiation points under cyclic stress conditions. Figure 5 illustrates the von Mises stress fields generated in the steel blade under peak-load conditions. Stress concentration zones were observed at the blade tip and around the bolt-hole interfaces. The maximum recorded von Mises stress was 152.8 MPa, which remained within the material's yield limit, suggesting a stable structural response under short-term operational loads. In contrast, the polymer blade (Figure 6) displayed a more diffuse stress distribution with a peak of 96.4 MPa, but with significant local deformation, indicative of viscoelastic strain accumulation.

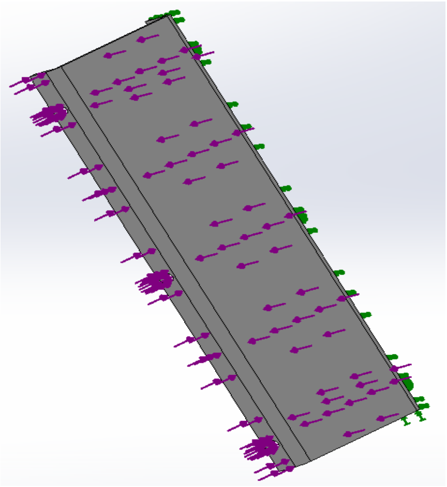

Fig. 1. *Fatigue-stress simulation in the steel-blade structure*

Fatigue simulations under cyclic loading revealed notable differences in damage evolution between the two materials. In the case of the steel blade (Figure 2), the fatigue life exceeded 1.2 × 10^6 cycles in most regions, with localized damage near the leading edge where repeated impact occurs. The corresponding damage percentage remained below 30% after the simulated operational period, suggesting high endurance and slow degradation.

Figure 2 presents a cumulative-damage model, expressed as a percentage, indicating the progressive material degradation caused by fatigue cycles. It highlights the most vulnerable regions of the blade geometry.

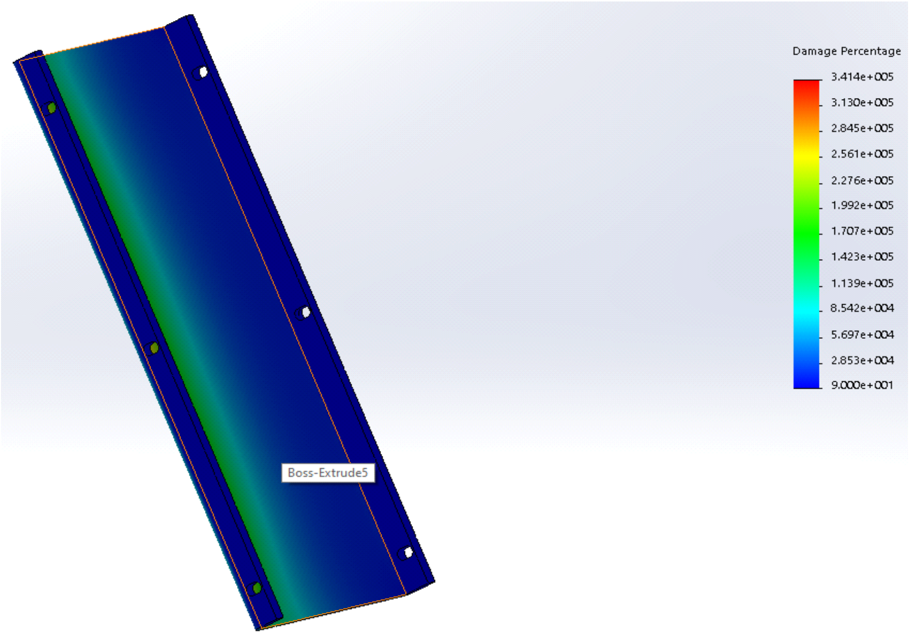

Fig. 2. *Damage distribution map for the steel blade under cyclic loading*

For the polymer variant (Figure 3), fatigue life predictions were considerably lower, with critical damage zones concentrated around the bolt connections, where cumulative fatigue damage reached 85-95% after equivalent loading cycles. The image highlights long-term structural degradation, indicating susceptibility to crack initiation in regions affected by stress concentration and material compliance. These findings confirm the reduced fatigue endurance of the polymer blade, despite its inherent capacity to absorb dynamic stresses.

Figure 4 displays the mechanical response of the blade when subjected to operational forces. The analysis helps identify the primary stress-bearing zones and validate its structural stability under real-use scenarios. Total deformation analysis (Figure 4) showed a maximum displacement of 1.4 mm for the steel blade and 4.9 mm for the polymer version under the same loading conditions. While the latter remained structurally intact, the large deformation may lead to dimensional instability and operational inaccuracy over time. The steel variant preserved its geometric integrity, supporting its suitability for long-term, high-precision cutting applications.

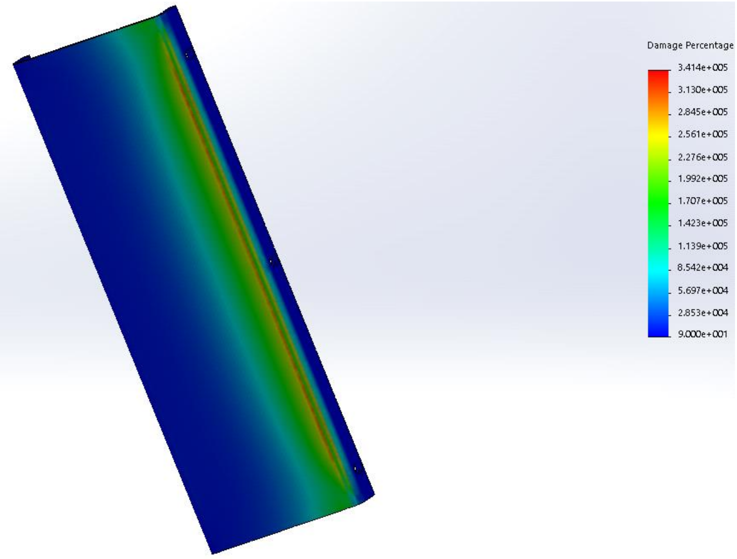

Fig. 3. *Fatigue failure prediction in the polymer blade around connection zones*

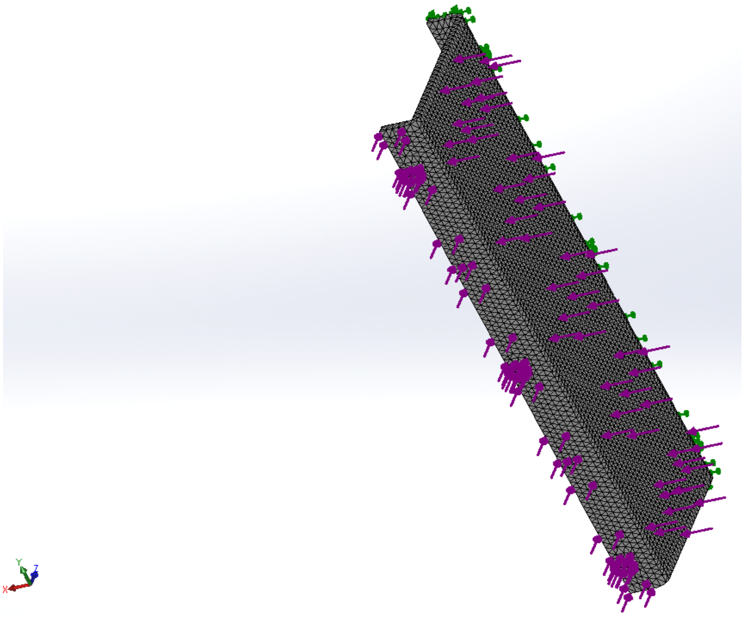

Fig. 4. *Total deformation of steel and polymer blades under load*

The combined stress and fatigue results highlight the superior structural reliability of the steel blade under repeated mechanical loads. Although the polymer blade offers reduced weight and lower production costs, its limited fatigue resistance and deformation under stress restrict its applicability in high-demand environments. These insights are critical for guiding material selection and structural optimization for future implementations.

Overall, the study confirms that FEA-based simulations provide valuable predictive insights into the operational lifespan and mechanical behavior of blade components used in vegetation-clearing systems. The integrated use of stress analysis and fatigue modeling enables targeted design adjustments to enhance safety and performance.

In Figure 5, the stress-distribution map illustrates the equivalent (von Mises) stress experienced by the blade under peak-load conditions. The simulation assists in assessing material yield risk and overall structural performance.

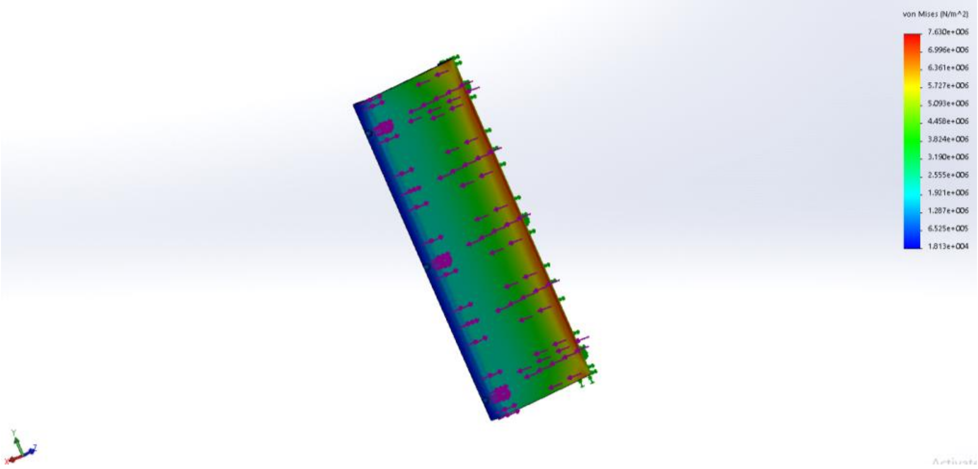

Fig. 5. *Von Mises stress distribution in the structural blade under operational force*

3. Conclusions

This study presents a comparative numerical investigation of two structural blade variants designed for mechanical vegetation-clearing systems. Using finite element analysis, the research assesses von Mises stress distributions, fatigue life, and deformation responses under identical cyclic loading conditions.

The results demonstrate that the steel blade exhibits superior fatigue resistance, lower deformation, and a more favourable stress profile. It maintains structural integrity over extended simulated cycles, confirming its suitability for high-stress applications where durability and dimensional stability are critical. In contrast, the polymer blade, while advantageous in terms of weight and flexibility, shows accelerated fatigue damage and significantly greater deformation, limiting its effectiveness in demanding operational environments.

By combining stress and fatigue analyses, the study underscores the importance of both material selection and geometry optimization in the design of cutting components. The methodology also validates the use of finite element simulation as a reliable tool for performance prediction and early failure detection.

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