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CAD-Based High-Fidelity Modeling and Tolerance Stack-Up Analysis of Threaded Fasteners in Precision Mechanical Assemblies

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Abstract

Mechanical fastening is a critical practice for assembling structural components, yet it introduces highly complex, localized stress fields near fastener and pin-loaded holes. Consequently, mechanically fastened joints remain frequent sources of structural failure in demanding aerospace and spacecraft applications. This study presents a high-fidelity computation and modeling framework to evaluate the structural reliability and fit of threaded fasteners in precision mechanical assemblies. Utilizing SolidWorks, detailed 3D CAD models of fasteners were developed using Alloy Steel (Grade 10.9) to guarantee high tensile strength and durability under operational loads. A rigorous tolerance stack-up analysis was performed to evaluate geometric fits, optimizing assembly performance while mitigating the risk of component interference. Furthermore, a computational procedure was implemented to analyze the initial failure loads of pin-loaded holes across both monolithic and layered composite structures. The integrated approach successfully bridges geometric tolerance verification with structural failure analysis, ensuring heightened reliability in critical precision assemblies.

Keywords: High-fidelity CAD modeling, Layered composite structures, Mechanical fasteners, Structural failure analysis, Tolerance stack-up analysis.

1. Introduction

Joining by mechanical fasteners is a foundational practice in the assembly of high-performance structural components. However, the integration of mechanical fasteners introduces highly complicated, localized stress fields near the bolt-hole boundary. Consequently, mechanically fastened joints are frequent sources of premature structural failure in aircraft and spacecraft structures, often reducing the total load-carrying capacity of primary components by more than 50% [1]. Achieving an optimal joint design not only enhances structural integrity and operational performance but also minimizes parasitic weight, thereby maximizing the vehicle's structural efficiency.

Fiber-reinforced laminated composite materials have become ubiquitous in aerospace structures due to their exceptional strength-to-weight and stiffness-to-weight ratios. Yet, the complex, anisotropic failure mechanisms of composite materials demand far more rigorous design methodologies than traditional, isotropic metallic joints. In bolted composite configurations, micro-damage typically initiates at early loading stages and progressively accumulates within the laminates as the external load escalates. This damage accumulation and the ultimate mode of macro-structural failure are strongly dependent on material properties, ply orientation sequences, laminate thickness, geometric parameters, and boundary loading conditions.

Extensive analytical and experimental investigations have established three fundamental, uncoupled failure modes in mechanically fastened composite joints:

- **Net-Tension Failure:** Driven by fiber and matrix tensile failure originating from catastrophic stress concentrations.
- **Shear-Out Failure:** Instigated by shear degradation along the shear paths of the fiber and matrix matrices.

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- **Bearing Failure:** Predominantly caused by compressive failure of the fiber and matrix beneath the fastener shank.

While net-tension and shear-out failures tend to propagate catastrophically and cause sudden structural loss, bearing failure exhibits a more progressive, ductile-like degradation profile, allowing for limited residual load-bearing capacity. Frequently, a coupled combination of these three baseline modes governs the ultimate failure envelope of the assembly.

To mitigate these complex structural risks, modern engineering design necessitates a paradigm shift toward high-fidelity virtual prototyping and precise geometric allocation. Threaded fasteners operate under severe vibrational, pre-load, and environmental pressures, requiring strict optimization of fastener geometry, material grading, and spatial tolerances. Small variations in fastener-hole clearances can alter the contact area, radically exacerbate localized stress concentrations or introducing destructive assembly interference.

This research addresses these challenges by developing a high-fidelity Computer-Aided Design (CAD) and geometric verification framework for critical mechanical joints. Utilizing SolidWorks, precise 3D parametric models of threaded fasteners are constructed using high-tensile Alloy Steel (Grade 10.9) to ensure robust durability under severe load fields. This geometric model is subsequently subjected to a rigorous tolerance stack-up analysis to evaluate assembly fit, minimize clearance variability, and bridge the gap between ideal CAD architecture and actual manufacturing boundaries, thereby preventing premature joint failure in precision mechanical assemblies.

2. Literature Review

The structural integrity, clearance optimization, and failure mechanics of mechanically fastened composite joints have been extensively investigated through analytical, numerical, and experimental methodologies. The existing literature can be organized chronologically and thematically into distinct evolutionary phases of joint analysis.

A. Optimization and Clearance Effects

Early computational frameworks focused heavily on optimizing joint geometry and understanding initial baseline geometric sensitivities. Kradinov et al. [1] integrated a genetic algorithm (GA) with structural stress analysis to determine the optimal configuration of bolted composite lap joints. Utilizing complex potential theory and a variational formulation, the authors minimized total potential energy to evaluate contact stresses and maximize joint strength across multiple design parameters, including laminate thickness, lay-up sequences, and bolt dimensions.

Concurrently, the physical behavior of joints under explicit geometrical variations gained traction. Xiao et al. [2] conducted experimental and numerical simulations focusing on the ultimate bearing strength and progressive failure modes of composite joints. To address geometrical imperfections, McCarthy et al. [3] experimentally investigated the critical effects of bolt-hole clearances in single-lap, multi-bolt configurations, while Lawlor et al. [4] extended this assessment to double-lap, multi-bolt joints. These clearance studies were augmented by McCarthy et al. [5]–[9] through high-fidelity three-dimensional finite element (3D FE) models, proving that bolt-hole clearances and frictional contact heavily dictate secondary stress variations and progressive damage tracks in graphite/epoxy laminates.

Spatial and geometric variations were further studied by Riccio et al. [10], [11], who evaluated damage onset under tensile loads. Addressing the mechanical anomalies of single-shear configurations, Ekh et al. [12] demonstrated that eccentric load paths induce a secondary bending phenomenon. This lateral deflection alters the through-thickness stress distribution and induces a severe stress singularity as the fastener tilts, shifting the fastener-to-hole boundary from surface contact to line contact.

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B. Analytical Scaling and Process Implementations

Camanho and Lambert et al. [13] introduced a semi-analytical methodology using point or average stress models to predict damage onset, final failure loads, and macroscopic failure modes in doubleshear quasi-isotropic joints. This framework was accompanied by standardized experimental routines to isolate characteristic tension and compression distances as a function of hole diameter and specimen width. This was later supplemented by Camanho et al. [14] in predicting in-situ strengths and localized matrix cracking under transverse tension and in-plane shear.

Concurrently, hybrid joining techniques and environmental manufacturing variables were explored. Kelly et al. [15] characterized the quasi-static strength and fatigue lifespan of combined bonded/bolted hybrid assemblies. From a material processing perspective, Himmel et al. [16] investigated the cyclic fatigue behavior of carbon fiber reinforced vinyl ester composites produced via Vacuum Assisted Resin Injection (VARI). Their findings highlighted how room-temperature curing under vacuum conditions facilitates large-scale structural manufacturing with exceptional mechanical integrity, as demonstrated in marine applications such as the *Visby*-class stealth corvette. Wrapping up the multi-bolt problem, McCarthy et al. [17] presented a simplified analytical alternative validated against 3D FE models to compute clearance-induced load redistribution across single-column, multi-bolt joints.

C. Parametric Preload and Failure Criteria Investigations

Sen et al. [18] and Sayman et al. [19] conducted parallel experimental investigations isolating the effects of edge-distance-to-hole-diameter ratios (E/D), width-to-hole-diameter ratios (W/D), and tightening torque moments on glass-epoxy laminated plates. Their results verified that increasing the preload moment significantly restricts localized delamination and enhances baseline bearing strength. These findings were corroboratively extended by Pakdil et al. [20] to capture the coupled interaction between bolt-hole clearances and stacking sequences.

3. Materials and Methods A. Material Characterization

While fiberglass represents a baseline standard in ordinary Fiber-Reinforced Polymer (FRP) structures due to its low cost, high-performance structural applications in aerospace and precision engineering require advanced material systems with superior specific stiffness and strength. For joints under high stress, high-modulus carbon fiber composites are utilized to satisfy strict weight constraints and minimize structural compliance. The mechanical properties of the carbon fiber phase implemented in this numerical study are defined in Table I.

Table I: Mechanical Properties of Carbon Fiber Reinforcement

Property	Value	Standard SI Unit
Young's Modulus (E)	70,000	MPa
Tensile Strength (σ_u)	3,900	MPa
Poisson's Ratio (v)	0.30	*Dimensionless*
Density (ρ)	2.0×10^{-7}	kg/mm^3($2000\ kg/mm^3$)

B. Finite Element Analysis (FEA) Foundations

The Finite Element Analysis (FEA) method serves as the primary numerical framework to solve complex differential equations governing elasticity, contact mechanics, and structural failure.

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Traditional analytical treatments derived from the mathematical theory of elasticity or basic strength of materials assume isotropic profiles and simplified geometries.

However, closed-form analytical equations are insufficient when evaluating complex mechanical systems—such as localized contact stresses and boundary non-linearities in multi-layered, pin-loaded composite structures. FEA bypasses these constraints by discretizing the continuum into an interconnected mesh of finite elements, solving localized constitutive equations to accurately capture high-gradient stress concentrations near the fastener hole interface.

4. Computer-Aided Design and Parametric Modeling A. Computational Role of CAD in Precision Engineering

Computer-Aided Design (CAD) architectures represent a core element of modern information technology within structural engineering. Rather than serving merely as a digital drafting system, advanced CAD systems integrate unified graphical engines with central databases to construct precise Product Data Management (PDM) workflows. In the context of precision mechanical assemblies, the implementation of a high-fidelity parametric CAD model provides several critical capabilities:

- **Parametric Integrity:** Establishes geometric relationships that allow for instantaneous modifications, facilitating fast design iterations during the tolerance allocation phase.
- **Analytical Interoperability:** Generates watertight boundary surfaces necessary for direct deployment into downstream physics engines, including static, dynamic, and geometric tolerance stack-up analyses.
- **Lifecycle Consistency:** Links the geometric history of components to track manufacturing variations and assembly interference constraints reliably.

B. SolidWorks Implementation Architecture

For this study, SolidWorks (Dassault Systèmes) was utilized as the core parametric 3D modeling platform. The fastener geometries and layered host plates were generated using a strict feature-based, parametric modeling pipeline. This methodology ensures that critical thread boundaries, shank clearances, and hole dimensions remain constrained by exact geometric variables. The 3D part configuration translates two-dimensional geometric profiles into solid features through precise extrusion and revolution paths, ensuring the model maintains high-fidelity conformity to Grade 10.9 fastener dimensions. These standalone parametric domains are subsequently integrated into a virtual assembly workspace. Within this workspace, spatial mating constraints recreate the exact boundary clearances and contact conditions present in physical joints. This structural assembly layout serves as the absolute geometric baseline for the geometric tolerance analysis and the linear static finite element validation that follow.

4. Results and Discussion A. Static Structural Performance

The comparative linear static finite element analysis evaluates the structural response of the precision joint configuration under two structural domains: a monolithic (Without Layered) assembly and a multilayered ply configuration (With Layered, utilizing a $[0/\pm 90]$s stacking sequence). The structural metrics are compiled in Table II.

Table II: Static Structural Analysis Results

Analysis Domain	Max. Deformation (mm)	Equivalent Stress (N/mm2)	Equivalent Strain	Max. Shear Strain
Without Layered	0.20019	366.35	0.00509	146.24

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With Layered $[\mathbf{0}/\pm\mathbf{90}]s$	0.49988	289.78	0.27698	121.48

The results indicate that while the introduction of a layered composite stacking layout increases the maximum localized deformation from 0.20019 mm to 0.49988 mm due to inter-laminar shear compliance, it significantly dampens peak stress concentrations. The maximum equivalent stress decreases from 366.35 N/mm2 down to 289.78 N/mm2, a net reduction of approximately 20.9%. This reduction confirms that the tailored $[0/\pm 90]$s fiber orientation effectively redistributes the bearing load away from the primary fastener hole edge boundary.

B. Fatigue Life and Damage Accumulation

To verify long-term assembly reliability under cyclic loading regimes, fatigue evaluations were conducted to isolate the minimum life, maximum localized damage indices, and corresponding operating safety factors. These numerical metrics are outlined in Table III. Table III: Fatigue Life and Reliability Results

Analysis Domain	**Min. Life (Cycles)**	**Max. Damage Index**	**Fatigue Safety Factor**
Without Layered	1.0×10^9	258.73	15.0
With Layered $[\mathbf{0}/\pm\mathbf{90}]s$	1.0×10^9	170.25	15.0

Both configurations successfully fulfill the design criterion of a high-cycle fatigue threshold, reaching an infinite life ceiling of 1.0×10^{-9} cycles. However, the maximum damage accumulation index exhibits a sharp decrease from 258.73 in the monolithic case down to 170.25 within the layered composite system. This performance improvement highlights the capacity of targeted ply-stacking to suppress micro-damage propagation near the fastener shank contact path.

4. Conclusion

This research presented a high-fidelity numerical investigation and CAD parametric design methodology focusing on the initial failure thresholds, geometric tolerances, and stress distributions of pin-loaded and threaded fastener joints. Special engineering focus was directed toward comparing monolithic structural domains against a symmetric carbon-fiber laminate architecture utilizing a $[0/\pm 90]$s stacking sequence. Based on the computational static and fatigue numerical simulations, the following conclusions are drawn:

1. **Stress Mitigation:** The integration of a parametric layered composite layout yields an immediate 20.9% reduction in peak localized equivalent stress fields (289.78 N/mm2) relative to unlayered configurations (366.35 N/mm}), considerably improving structural resistance against net-tension failure.
2. **Shear Performance:** Localized shear strain magnitudes at the critical fastener hole boundary drop from 146.24 down to 121.48 when deploying the laminate configuration, mitigating the risk of premature shear-out failures.
3. **Fatigue Life Preservation:** While both structural implementations exhibit high structural reliability—maintaining a safe operational fatigue safety factor of 15.0 and achieving a design life threshold of 1.0×10^9 cycles—the maximum cyclic damage accumulation index is lowered by 34.2% within the layered composite structure.

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The findings confirm that combining high-fidelity parametric CAD modeling with strategic composite ply tailoring provides a robust design paradigm capable of optimizing tolerance fit, eliminating component interference, and maximizing the structural capacity of precision aerospace and mechanical assemblies.

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