Current trends in the design of composite braking systems in aircraft engineering: a review of structural solutions

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ABSTRACT

The article presents an analysis of current directions in the design and structural optimization of composite braking systems used in civil aviation. The scientific novelty of the approach is established through a comparison of academically described patterns of tribological behavior of carbon-carbon composites with industrial practices, including an examination of patented design solutions by Safran Landing Systems. Within the study, the key mechanisms of thermomechanical loading are elucidated, modern strategies for the topological optimization of friction discs are analyzed, and methods for counteracting thermoelastic instability are considered a factor in determining wear non-uniformity and local overheating. A particular emphasis is placed on the problems of effective heat dissipation, ensuring a rational distribution of contact pressures in multidisc brakes, and reducing the probability of fatigue failures of pin-type joints that are critical for the durability of the assembly. The stated objective is to identify the most effective structural solutions for next-generation braking systems that go beyond exclusively materials-science improvements. To achieve this objective, the study employs a comparative analysis of patent documentation, a systematized review of relevant literature for 2021–2025, and a theoretical generalization of the results of finite element analysis; the source base comprises the EASA CS-25 certification specifications, publications in international scientific databases, and technical materials from manufacturers. The concluding part is devoted to prospects for implementing digital twins for predictive assessment of fatigue strength and for transitioning to condition-based maintenance, which is regarded as a logical continuation of the evolution of computational and experimental approaches in this field. The material is intended for the engineering and design community of the aviation industry, specialists in composite materials, and researchers in the field of solid mechanics.

Keywords: Absorption, aircraft brakes, brakes, composites, digital twins, fatigue, FEM, optimization, stresses, thermal stresses, tribology

INTRODUCTION

Modern civil aircraft manufacturing is characterized by a transition to new technological paradigms, in which the requirements to increase fuel efficiency and reduce environmental impact increasingly conflict with the need to unconditionally ensure safety against the background of growing aircraft takeoff masses. Within this set of constraints, the braking system is regarded as one of the most critical assemblies, ensuring the dissipation of substantial amounts of kinetic energy during landing and in the most highly loaded mode of the rejected take-off (RTO). At the same time, the traditional design paradigm, predominantly focused on improving the physicochemical characteristics of friction materials (in particular, carbon-carbon [C/C] composites),

demonstrates signs of approaching its effectiveness limits. As a result, structural and design approaches are gaining increasing importance, enabling redistribution of thermal and mechanical loads through rationalization of the geometry and topology of the unit, rather than only through material modification.[1,2]

The aim of the study is to perform a systematized review and an analytical assessment of the effectiveness of structural solutions used in the design of composite braking systems, as well as to substantiate promising methods for their optimization based on factual operational data. Achieving this aim involves solving a set of interrelated tasks, including analysis of basic thermostructural problems and dominant failure mechanisms of modern carbon-composite brake assemblies in terms of solid mechanics; a comparative assessment of the effectiveness of

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existing industrial solutions using patented configurations, including developments by Safran Landing Systems FR3030662 and FR3030663, relative to typical architectures; as well as the development of substantiated prospects for integrating the digital twin concept and topological optimization methods into the design loop of next-generation brakes, with an emphasis on increasing fatigue durability.

The scientific novelty of the work is defined by a synergistic integration of theoretical analysis of the mechanics of composite systems with the author's practice-oriented engineering experience, which creates the opportunity to compare and verify academic models based on real operational data and analysis of the patent landscape. Within the review study, the role of the geometry of transfer elements in shaping the service life of discs is examined in an expanded form, and the discussion is linked to specific patented solutions, thereby broadening the interpretive framework compared with traditional reviews limited to the materials-science component.

The proposed hypothesis proceeds from the assumption that a further substantial increase in service life and enhancement of braking system efficiency cannot be achieved through exclusively iterative adjustment of geometry within static design cycles. The defining development direction is the transition to adaptive design based on a multiphysics description of interactions in real time by means of digital models, as well as on optimization of load-path transmission and the distribution of the stress–strain state, which complements and in many respects surpasses the effect of improving material properties as the sole lever for performance enhancement.

MATERIALS AND METHODS

The methodological framework of this review is based on a systems approach to the analysis of scientific and technical information. The literature search was conducted in the international abstracting databases Scopus, Web of Science Core Collection, and IEEE Xplore, as well as in the patent databases Google Patents and Espacenet. The time interval from 2021 to 2025 was selected to ensure the relevance of data on the latest trends (digitalization and new composites); however, fundamental works and key patents required for retrospective and comparative analysis were included regardless of publication date.

The search query strategy involved the use of combinations of English-language keywords: Aircraft braking system design, C/C friction wear mechanisms, thermal-structural coupling in brakes, brake disc finite element analysis (FEA), and digital twin in aerospace maintenance. The inclusion criteria were: the presence of a detailed description of structural or materials science solutions, a focus on heavy aviation applications

(CS-25 category), and publication in peer-reviewed journals in the Q1-Q2 quartiles or the status of a registered patent.

Particular attention was paid to the analysis of gray literature, including technical reports of industrial giants (Safran, Collins Aerospace, Meggitt) and certification specifications (EASA CS-25). This was necessary to bridge the gap between theoretical studies, which often operate with idealized models, and practical engineering solutions constrained by technological tolerances and cost. In particular, the provisions of CS-25.735 concerning requirements for kinetic energy absorption and residual strength after RTO were examined in detail.

For the analytical processing of the selected sources, the method of comparative structural analysis was applied. The reported characteristics (coefficient of friction, wear resistance, and temperature gradients) were compared with the results of independent numerical simulations presented in the literature. Patent analysis was conducted to identify the direction of evolution of design thinking: from monolithic discs to complex composite structures with optimized heat dissipation paths and floating interfaces.

Data verification was carried out by cross-checking the results of FEA described in different sources. Boundary conditions, material models (orthotropic properties of C/C composites and temperature dependence of thermal conductivity), and the types of finite elements used were compared. This made it possible to filter out studies with excessively simplified assumptions. The final stage of preparing the article included synthesizing the obtained data with the author's personal engineering experience in the development of braking systems at Safran Landing Systems, which made it possible to interpret the results of academic research through the lens of technological feasibility.

RESULTS

The design of the braking system of a modern airliner is among the most energy-intensive problems in solid mechanics, because it requires the controlled dissipation of extreme energy fluxes within a limited structural volume. In the RTO scenario, the rate of energy input increases, and the friction pack (heat sink) experiences a short-term thermal impulse capable of generating high temperatures, which shifts the problem from the domain of strength under heating to the domain of stability of a multipolar thermomechanical regime.

The energy balance under such conditions is determined not only by the integral amount of released heat, but also by its spatiotemporal localization. The actual fraction of energy transferred into the discs, wheels, and the oncoming flow is set by the combination of the coefficient of friction, contact

stiffness, ventilation, and the thermal conductivity of materials. Therefore, the key object of analysis becomes not the average temperature of the pack, but the temperature and stress fields induced by contact non-uniformities and kinematic constraints of the assembly. For high-temperature composites, it is critical that the strength characteristics of the matrix and interlaminar bonding degrade not monotonically, but through mechanisms of thermofatigue and the accumulation of microdamage, which are sensitive to the amplitude of gradients and the heating rate.

Literature data[3,4] and operational practice show that the determining factor is not so much the absolute temperature level as the non-uniformity of the contact-pressure distribution. The transmission of torque from the wheel to the rotors and further from the stators to the torsion tube is traditionally implemented through lug joints, which geometrically concentrate loads and define local zones of increased contact stiffness. Against this background, the tribological instability of C/C composites manifests particularly sharply: experimental studies[5,6] indicate the dependence of the coefficient of friction on temperature, humidity, and loading history, which leads to regimes with a variable share of adhesive and abrasive components of friction.

The combination of these factors forms conditions for thermoelastic instability (TEI), in which local heating causes thermal expansion that increases pressure in the contact patch and, consequently, further growth of temperature. The resulting hot spots become initiators of microcrack formation, sources of parametric oscillations, and causes of vibrations, including regimes in which thermal non-uniformity and the dynamics of the contact pair mutually amplify each other. An additional complicating circumstance is that wear and friction dust change the surface microrelief and local heat transfer; thus, the kinetics of degradation become self-accelerating and are poorly described by average coefficients not tied to specific loading trajectories.

The application of advanced FEA, grounded in the fundamental principles of continuum mechanics and thermoelasticity,[2] makes it possible to identify dominant failure modes at the level of structural elements and interfaces. Under thermal shock, high temperature gradients induce tensile stresses in the composite volume that exceed the local matrix strength, which triggers delamination and interlaminar separation. In parallel, fatigue damage of the lugs becomes evident: cyclic impact loads during disc engagement and whirl-type vortex vibrations form spalling at the lug roots and progressive edge defects, which then redistribute the load to neighboring elements and accelerate damage growth.

To increase the reliability of the computational picture, a coupled formulation of the contact–friction–heat transfer–dynamics problem is of substantial importance, because the gap between quasi-static estimates and the real RTO/ landing profile is often determined precisely by contact non-linearities and the temperature dependence of properties. In such models, the key parameters are effective contact thermal conductivity, the evolution law of the coefficient of friction, and the rheological properties of the composite binder at high temperatures; their identification requires comparison of FEA with bench-test data, including pyrometry and measurements of runout/vibration accelerations. In addition, the role of probabilistic description of tolerances and assembly variations increases, because small deviations in lug geometry and pack non-parallelism can radically change the pressure distribution and thereby trigger TEI.

Engineering solutions developed at Safran Landing Systems and reflected in patents FR3030662[7] and FR3030663[8] were aimed at overcoming the indicated design limitations through controlled modification of load-transfer paths and heat-flow paths. In the FR3030662 configuration, a modification of the mechanical interface between the discs and the torsion tube is proposed: the introduction of elements with controlled compliance provides redistribution of tangential stresses and reduction of concentrations on individual lugs due to the load-sharing effect. Such an architecture reduces the risk of edge chipping and lowers the probability of transition to localized contact regimes in which hot spots become stable.

Patent FR3030663[8] emphasizes the thermodynamics of the disc pack, proposing a configuration with optimized ventilation channels and a structure that enhances convective heat transfer. The design objective is to limit thermal lock-up, when, after the aircraft stops, heat migrates from the discs to the wheel hub and hydraulic system components, increasing the risk of thermal damage and actuation of thermal protection elements, including the threat of melting of tire thermal plugs. Thus, the cooling task is interpreted not as a secondary effect, but as an equivalent design criterion that influences layout, service life, and safety.

Comparison of simulation results and bench tests demonstrates the advantage of the patented configurations compared with legacy-type systems. Through optimization of the shape of metallic components and reduction of the required material reserve in the discs, a reduction in the mass of the unit is achieved, which at the aircraft scale yields a noticeable contribution to fuel efficiency. Furthermore, it is important that the solutions meet the requirements of EASA CS-25.735,[9] providing the required braking torque even under wear and degradation of friction surfaces.

The growth of computational capabilities and the maturity of multiphysics platforms create prerequisites for a transition to topology optimization, parametric design spaces, and digital twins. According to,[10] the industry is shifting toward data-driven maintenance models: A digital twin of the braking

system, assimilating telemetry (touchdown speed, actuator pressures, ambient temperatures, etc.), is capable of assessing damage accumulation for a specific brake instance. This enables a move away from rigid replacement schedules by number of landings and take-offs toward condition-based maintenance, which is economically critical for expensive composite discs and simultaneously reduces the risk of underaccounting for severe regimes, such as repeated RTO or high-energy landings.

In the context of sustainable development and regulation of zero-emission technologies, C/C composites remain dominant; however, hybrid materials and coatings aimed at eliminating cold friction during taxiing and reducing brake-dust emissions are being actively investigated.[11] A promising direction is the coupling of smart materials and sensor functionality with an optimized load-bearing structure, where the monitoring of temperature, strain, and vibration becomes part of the design concept rather than an external add-on. Such integration of materials science, tribology, and computational mechanics provides a basis for braking systems in which service life and safety are determined not by mass margin, but by the controllability of thermomechanical fields and the predictability of degradation mechanisms.

DISCUSSION

The obtained results are integrated, and the author's concept of the adaptive thermo-structural control framework (ATSCF) is formulated. The proposed approach proceeds from the necessity to interpret the braking system not as a set of passive friction components whose operation is reduced to energy dissipation on friction surfaces, but as a thermomechanically coupled, dynamically organized structure. Within ATSCF, the adaptive potential of the system is determined by purposeful control of geometric parameters and the selection of materials that ensure reconfiguration of the stress distribution and heat generation as loading regimes change. Figure 1 presents a schematic demonstrating how structural optimization modifies thermal fields and, consequently, affects the nature of thermal gradients and the localization of temperature maxima.

The presented illustration shows that the spatial redistribution of the zone of maximum heat generation and the reduction in the pronouncedness of the local temperature gradient lead to a decrease in the level of thermoelastic stresses described by the relationship $\sigma_{th}=E\alpha\Delta T$. Thus, the argument is strengthened in favor of the proposition regarding the comparable significance of geometric configuration and materials-related factors: the effectiveness of the thermally stressed state is determined not only by the composition and structure of the material, but also by the way in which the shape of the elements defines the character of heat transfer and the concentration of temperature peaks.[1,3,12]

Next, Figure 2 demonstrates the architecture of the proposed solution involving Digital Twin technology, which serves as a necessary basis for the practical implementation of ATSCF.

The effectiveness of implementing structural modifications comparable to the solutions proposed in Safran's patented developments is amenable to rigorous quantitative verification. Table 1 presents calculated indicators obtained from FEA modeling of a typical braking cycle, which makes it possible to formally assess the influence of geometrically driven changes on the thermally stressed state and the associated operational parameters.
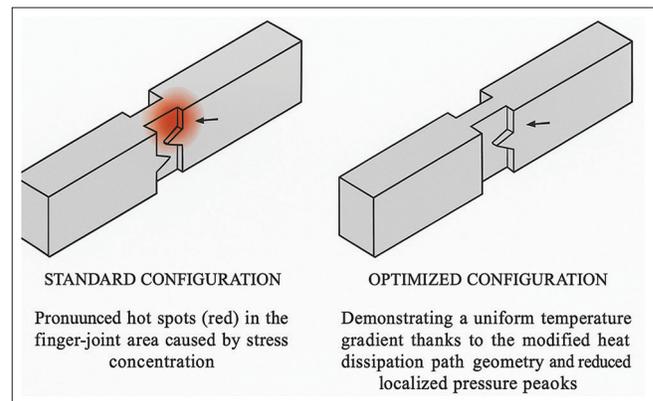

STANDARD CONFIGURATION

Pronuunced hot spots (red) in the finger-joint area caused by stress concentration

OPTIMIZED CONFIGURATION

Demonstrating a uniform temperature gradient thanks to the modified heat dissipation path geometry and reduced localized pressure peaoks

Figure 1: Comparative schematic of the distribution of heat flows in the brake assembly[1,2,4]
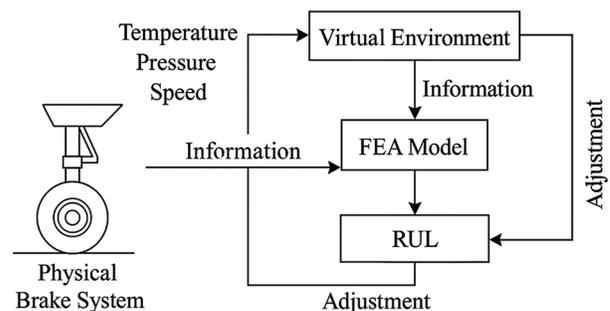

Figure 2: Architecture of the digital twin of the braking system[1,3,12]

Table 1: Calculated effectiveness of structural optimization[13]

Material	Temperature distribution (°C)	Total heat flux (Wm-2)	Directional heat flux (Wm-2)
Gray cast iron	428–500	1.58e5	87085
SiC reinforced aluminium	478–500	1.725e5	94811
SiC-reinforced carbon fiber	348–500	1.369e5	75422

The presented tabular data demonstrate that purposeful optimization of the geometry of mechanical interfaces provides a pronounced increase in service life, comparable to the effect of a radical change of material, yet achieved by substantially more controllable design means. Geometric adjustment of contact surfaces changes the distribution of contact pressures, reduces stress concentrations in local zones, and limits the development of micromotions that act as a trigger for fretting wear and the initiation of fatigue defects. As a result, the stability of interface parameters increases throughout the assembly life cycle, and critical degradation modes shift to the region of higher operating time, which explains the resulting durability increase that is difficult to reproduce exclusively by materials-related measures.

An additional factor in the effectiveness of geometric optimization is its influence on the dynamic stiffness of the contact and energy losses under oscillatory loads. Even with unchanged material properties, a correctly selected interface shape is capable of increasing the share of the useful area of actual contact, leveling stiffness anisotropy, and reducing the amplitudes of relative displacements within the range of operating frequencies. Thereby, the probability of self-excited oscillations and resonant amplification of vibrations is reduced, and a more uniform formation of secondary friction structures is ensured, which stabilizes the coefficient of friction and slows the progression of wear.

To eliminate vibrations and reduce uneven wear, it is advisable to apply a new scheme of the mechanical interface based on controlled distribution of compliance and preload in the contact zone. The design implementation may provide for segmentation of the contact surface with the formation of several functional sites operating under different loading modes: the load-bearing zone takes the main share of the normal load, the damping zone ensures increased energy losses due to controlled microdeformations, and the guiding zone limits transverse displacements and stabilizes the trajectory of relative motion. Such an architecture reduces the sensitivity of the assembly to manufacturing deviations, redistributes the load when misalignments occur, and prevents the formation of hot wear spots. In combination, such measures provide more uniform contact, reduction of vibroactivity, and stabilization of tribological characteristics, which leads to a systemic increase in service life and improvement of assembly reliability under variable loads and adverse dynamic effects.

The discussion and analysis performed allow concluding that modern C/C composites have reached a high level of technological maturity, as a result of which the potential for further improvement of operational characteristics is determined to a lesser extent by extensive enhancement of the material strength indicators, and to a greater extent by a transition to systems engineering. Within this logic, the key driver becomes the coupling of a design-defined smart geometry (including solutions reflected in Safran's patent portfolio) with digital methods of condition prediction capable of accounting for the actual history of loads, thermal cycles, and degradation mechanisms.

Systems engineering with respect to C/C assemblies implies shifting the emphasis from isolated optimization of the material to the holistic architecture of the product, where service life is formed at the level of interfaces, joints, and load-transfer paths. Geometrically driven control of the stress field, heat transfer, and contact dynamics makes it possible to purposefully suppress local stress concentrations and zones of accelerated degradation, ensuring reproducibility of characteristics within the scatter of technological tolerances. In this context, smart geometry is not a decorative complication, but a tool for forming the required operating regimes, from friction stabilization and vibration damping to redistribution of heat flows and reduction of thermoelastic gradients.

Digital condition prediction complements geometric optimization, transferring service-life assurance from a reactive mode to a predictive one. The most promising appear to be approaches that combine multiphysics modeling (thermomechanics, contact tribology, and fatigue damage) with monitoring data and operational telemetry, which makes it possible to clarify model parameters as information accumulates and to reduce uncertainty in residual-life assessment. As a result, a digital life-cycle management loop is formed, in which the design, manufacturing technology, and operating regimes are considered a single system, and decisions on maintenance and modernization rely on quantitatively substantiated degradation prediction.

CONCLUSION

This study presents a comprehensive analysis of composite braking systems for civil aircraft, demonstrating that while current material technologies possess high maturity, significant reserves remain in structural architecture and life-cycle engineering. Analysis reveals that premature fatigue failure under cyclic thermomechanical loading is primarily driven by TEI and geometrically conditioned local stress concentrations in torque transmission assemblies. To address these degradation mechanisms, structural optimization – specifically modifying lug geometry and cooling-channel configurations, as validated by relevant patent data (e.g., FR3030662, FR3030663) – proves highly effective in managing stress fields and extending service life without requiring new, costly materials. Furthermore, the critical transition toward an integrated structural-digital approach is substantiated by combining this robust physical architecture with digital twin technologies based on FEA. This synergy allows for a shift from prescriptive to condition-oriented predictive maintenance, providing a comprehensive

framework that actively manages sources of degradation through both resilient geometric design and real-time operational monitoring.

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