Research Progress of CMC Structures for Advanced Engines in Vibration Stability and Flutter Analysis

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Abstract: Advanced propulsion systems experience critical challenges under extreme service conditions, including aerodynamic loads and thermal loads. Especially, flutter stability is a key bottleneck restricting the design and safe operation of hot structures in advanced propulsion systems employing ceramic matrix composites (CMCs). Compared to traditional nickel-based alloys, CMCs offer superior high-temperature resistance and specific strength, making them ideal for next-generation engine hot structures. The inherent anisotropy, heterogeneity, and complex nonlinear behavior of CMCs, coupled with extreme operating environments, result in strong multi-physics interactions, including aero-thermo-structural, thermo-mechanical, and damage-aeroelastic coupling. These complexities significantly complicate vibration stability and flutter analysis. The recent research progresses on these problems are systematically examined, focusing on multi-field coupling mechanisms, material constitutive and damage evolution models, multi-scale modeling methods, coupled solution strategies, and the influence of key parameters on flutter characteristics. The current challenges are highlighted, including the complexity of high-temperature nonlinear modeling, the efficiency of multi-field coupling calculations, and the multi-scale modeling of complex weaving structures. Finally, an outlook on future development directions is presented to provide theoretical support for the design and safety assessment of hot structures of advanced CMCs.

Key words: ceramic matrix composites (CMCs); vibration stability; flutter; multi-field coupling; advanced engines

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0 Introduction

Advanced propulsion systems in extremely service condition experience critical challenges[1], including the coupled aerodynamic loads and thermal loads. Due to the suddenness and catastrophic consequences, the issue of structural vibration stability has always been a key technical bottleneck. Especially the phenomenon of flutter has restricted the design and safe operation of hot structure in advanced power systems[2]. Flutter problem becomes more complex and dangerous in high temperature, pressure, and speed regimes, compared with conventional engines[3], due to the heating effect of aerothermal condition, high-level dynamic pressures, complicated boundary interactions and unsteady flow characteristics.

Since the 21st century, materials technology has become a global technological hotspot. The high-temperature materials are classified as the core in the program of "Materials Genome Initiative" in USA and key special projects on new materials of "The 13th Five-Year Plan" in China. Hot structures of advanced engines have to endure high tempera-

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ture, high pressure, and high speed conditions. However, the traditional nickel-based alloys have become unable to meet the requirements of the next-generation designs. Thus, ceramic matrix composites (CMCs), such as silicon carbide fiber-reinforced silicon carbide (SiC_f/SiC) or carbon fiber-reinforced silicon carbide (C_f/SiC), have become the focus of research due to their advantages in extreme environments. CMCs are composed of continuous fibers (such as C_f, SiC_f) as the reinforcing elements, with ceramics (such as SiC, Si_3N_4) as the matrix, and are fabricated through complex processes. Therefore, CMCs are usually recognized as the ideal materials for advanced engine hot structures due to their outstanding high-temperature resistance (working temperature exceeds 1 650 ℃), high specific strength and specific stiffness (with a density only 1/3 to 1/4 that of nickel-based super alloys), excellent thermal stability, oxidation and ablation resistance, and excellent thermal shock resistance[4]. CMCs have already been verified and put into initial application in advanced aerospace engine hot structures (such as combustion chamber, turbine guide vanes, etc.)[5]. The reliability and performance advantages in extreme high-temperature environments have laid the foundation for the development of the next-generation propulsion systems. The overall research framework on vibration stability and flutter analysis of advanced engine CMC hot structures is illustrated in Fig.1, highlighting the aerodynamic-structural-material coupling challenges, nonlinear response mechanisms, analysis methods, and future prospects.

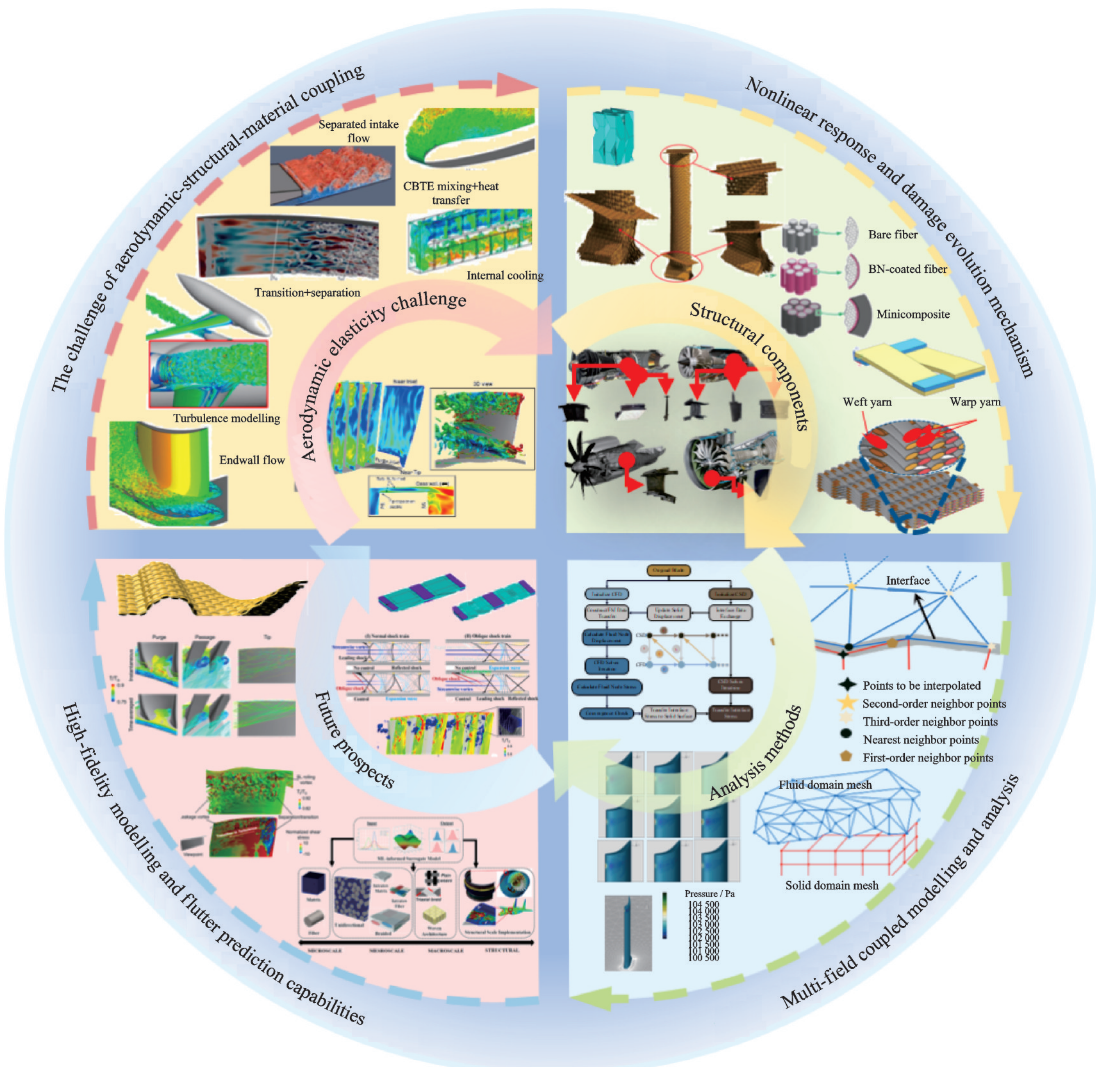

Fig.1 Framework of research progress in vibration stability and flutter analysis of the thermal end CMCs hot structures of advanced engine CMCs

The schematic diagram in Fig.2 illustrates both the applications and performance advantages of CMC hot structures for engines under different flight conditions[5]. In the 1990s, CMCs began to be industrialized. In the aerospace field, the Hi-Nicalon fibers reinforced SiC-based composite combustion chamber[6] developed by GE/Allison company could withstand a temperature of 1 316 ℃. The tail nozzle external regulating plate developed by the French SNECMA company[7] based on nD-C_f/SiC composite material was put into mass production in 1996. The SiC_f/SiC low-pressure turbine guide vanes jointly developed by General Electric and Rolls-Royce companies have been applied to the F-35 engine[8]. For instance, Mercury, Gemini, Apollo, Space shuttle, Draon2, Vostok, Soyuz, and Shenzhou are manned reentry vehicles with successful missions[5]. Furthermore, in the fields of energy and aerospace propulsion, CMCs are designed as the materials for thermal protection systems (TPSs) and thermal structures[9], which demonstrates the advantages of high energy conversion efficiency and low maintenance costs in extreme environments such as nuclear fusion reactors.

However, the vibration stability problem of an engine becomes more challenging when CMCs are used as the hot structure materials[10-12], due to the following reasons.

(1) Anisotropy: The mechanical and thermal physical properties show significant differences along the fiber direction, perpendicular to the fiber direction, and in the thickness direction.

(2) Inherent heterogeneity: The material consists of reinforcing fiber bundles, ceramic matrix, fiber/bulk interface, and inevitable pores and microcracks introduced during the manufacturing process. The non-uniform and discontinuous morphology caused the local stress concentration, uneven strain

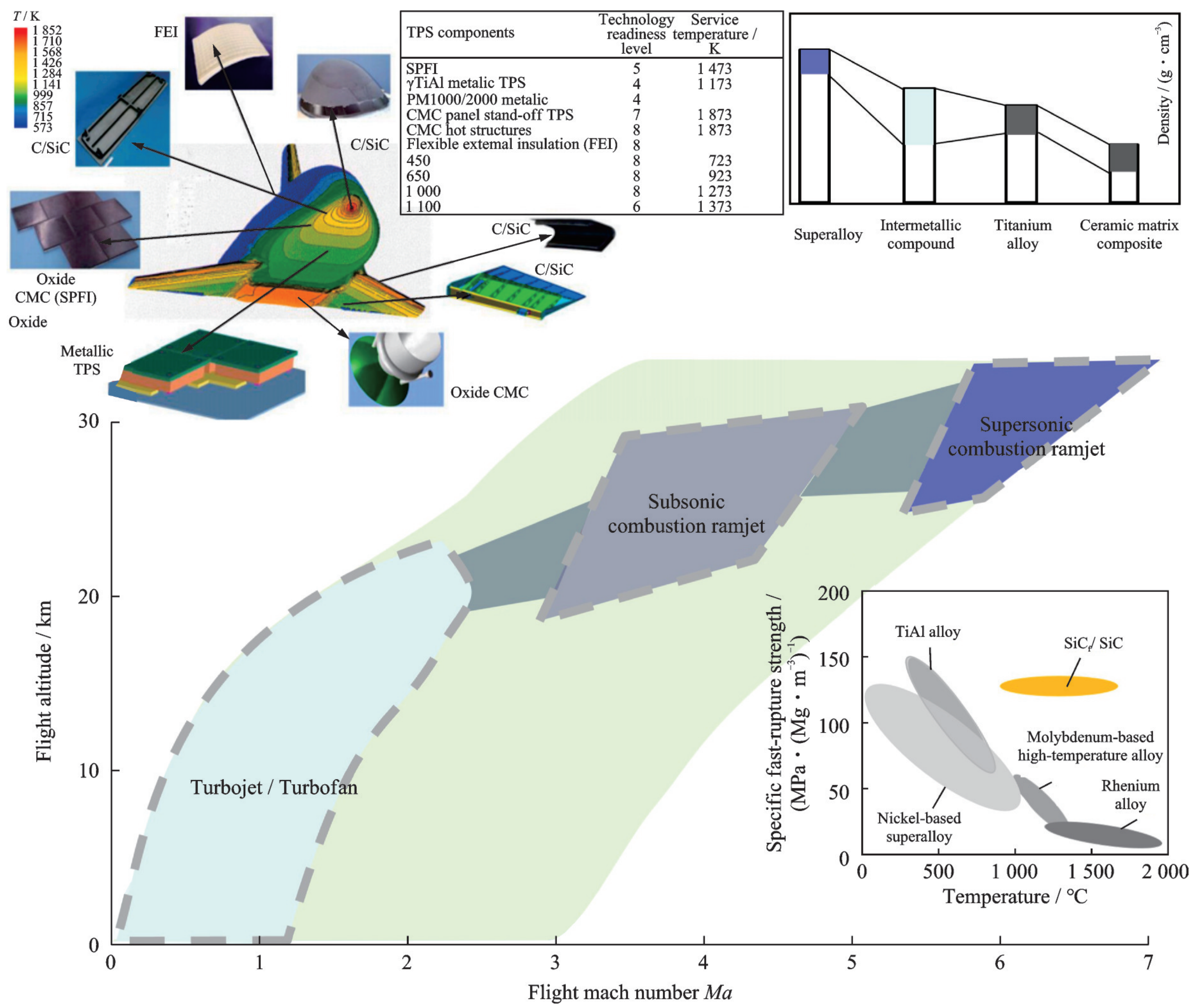

Fig.2　Schematic diagram of application and performance of CMC hot structure for engines under different flight conditions[5]

distribution, and the initiation and propagation of cracks closely.

(3) Complex nonlinear mechanical behavior[13]: Due to the gradual emergence and cumulative evolution of various fracture behaviour such as matrix cracking, interface debonding/sliding, fiber extraction, and fiber fracture, CMCs exhibit significant nonlinear stress-strain relationships, causing the effective modulus of the material to dynamically change with the loading history and damage state (low stress levels).

(4) Unique characteristics of fatigue, creep and fracture[14]: The fatigue damage mechanism under cyclic loading is different from those of metals, and it exhibits significant creep behavior and stress relaxation phenomena under high temperature and high stress environments, affecting the long-term dimensional stability of the structure.

(5) Sensitivity to high-temperature environments: High temperature not only directly alters its inherent mechanical properties and introduces negligible thermal stress, but also triggers complex interface and component oxidation problems, leading to the degradation of material properties.

In extreme operating environments with high temperatures, high pressures, and high speeds, the complex material properties of CMCs interact with the external environment, resulting in a strong multi-physics coupling effect among the external extreme aerodynamic flow field, thermal environment, structural deformation, and the internal physical and chemical responses of the materials, such as dynamic-thermal-structural coupling, thermal-thermal coupling, damage-vibration coupling, and multi-scale coupling[15-16]. These problems are often tangled, forming a much more complex problem, which becomes the core difficulty for accurately predicting vibration stability and flutter boundaries. Therefore, the multi-field coupling behaviors should be taken into account in aerodynamic elasticity analysis of CMC structures as follows.

(1) Aero-thermo-structural coupling: The intense dynamic pressure and heat flux generated by hypersonic airflow act jointly on the surface of the CMC structure, causing large deformations, vibrations, significant temperature increases, and temperature gradients. The deformation of the structure and the changes in the temperature field thereby affect the distribution of aerodynamic force and heat. Meanwhile, the sudden temperature change directly affects the material properties of CMCs, forming a complex thermal-mechanical coupling.

(2) Thermo-mechanical coupling: The mechanical properties of CMCs alter/vary with temperature[17]. These factors will directly affect the dynamic stiffness distribution, natural vibration frequency, and mode of the structure, thereby changing the aerodynamic elastic response characteristics.

(3) Damage-aeroelastic coupling: Under the influence of complex thermal and mechanical cyclic loads, various kinds of damage will be developed within the CMCs. The accumulation of these damages will lead to a significant decrease in the local and overall stiffness of the structure, changes in damping properties, and slight variations in mass. This will significantly affect the natural frequency and mode of vibration of the structure, and ultimately may greatly reduce the flutter critical speed of the structure or change the flutter mode. On the contrary, the large magnitude of vibrating deformation during flutter will generate alternating stresses, accelerating the evolution and expansion of fatigue damage within the CMC material.

(4) Multi-scale coupling: The macroscopic structural responses of CMCs, such as deformation, vibration, and flutter instability, depend on their mechanical behaviors at the mesoscopic scale and the microscopic scale as well as the thermal/chemical reaction kinetics[18]. Therefore, the establishment of cross-scale analysis models and methods that can effectively transfer information at different scales, which is required for accurate prediction of the macroscopic aerodynamic elastic behavior[19-20], linking the microscopic material changes with the macroscopic structural responses.

The numerous coupled effects interweave and dynamically evolve, significantly increasing the complexity of vibration stability and flutter analysis of the CMC hot structures. Inadequate knowledge of these mechanisms, especially the nonlinear degradation of CMC performance under high temperatures, will lead to incorrect judgments of the flutter boundary, thereby misjudging the structural integrity of the dynamic system. Therefore, it is necessary to carry out in-depth research on the vibration stability problem of CMC structure under multi-field coupling conditions, revealing its inherent physical mechanisms and developing high-fidelity coupling analysis methods.

The review paper analyzes the severe challenges that extreme aerodynamic heating environments pose to the material properties and structural integrity. It discusses the close coupling effect between high dynamic pressure, strong unsteady aerodynamic forces, and material damage (Subsection 1.2), as well as the unique challenges encountered in designing CMC thermal structures under such extreme thermal conditions (Subsection 1.3). Furthermore, the complex physical behaviour of CMCs was examined in depth, with particular attention to hierarchical structural coupling (Subsection 2.1), nonlinear constitutive relationships (Subsection 2.2), significant tension-compression asymmetry (Subsection 2.3), thermal bridging and crack propagation (Subsection 2.4), and damage coupling triggered by defects (Subsection 2.5). Based on this, systematic modeling and analysis techniques for addressing these complexities were proposed. The core lies in constructing a coupling analysis framework (Subsection 3.1) that encompasses multiple physical fields such as aerodynamic-thermal coupling (Subsection 3.2), thermodynamic-mechanical coupling (Subsection 3.3), and damage-aerodynamic elastic coupling (Subsection 3.4). Special emphasis was placed on the importance of multi-scale coupling modeling methods (Subsection 3.5) in handling material heterogeneity and damage evolution, and the coupling flutter analysis method for predicting structural stability (Subsection 3.6) was discussed. Finally, after summarizing the aforementioned research results, this chapter aims to outline the overall picture and development trajectory of this field.

1 Aerodynamic Elasticity Challenge

Aeroelasticity has been extensively studied in traditional aircraft and hypersonic vehicles for decades, where classical phenomena such as flutter, divergence, and control surface reversal are well documented. These problems are usually investigated through fluid-structure coupling models, nonlinear dynamic analysis, and wind tunnel tests. However, in advanced propulsion engines, aeroelastic issues exhibit distinct complexities due to high operating temperatures, high rotational speeds, and confined internal flow environments. Therefore, they require targeted analysis that integrates new materials and specialized structural designs. The issue of the coupling mechanism between aerodynamic instability and elastic instability is particularly prominent. The current research mainly focuses on areas such as multi-physics field coupling modeling, nonlinear material behavior description, and high-temperature dynamic response prediction. Due to factors such as the nonlinear characteristics of materials, the difficulty in accurately capturing high-temperature flow fields, and the scarcity of experimental verification data, high-fidelity, multi-field strong coupling flutter modeling still faces many challenges. The underlying physical mechanism responsible for flutter and related instability phenomena in CMC structures can be summarized as the following three interwoven and closely coupled key factors.

(1) Extreme aerodynamic heating in hot-end regions and the resulting degradation of CMC mechanical properties.

(2) Coupling between strong unsteady aerodynamics (e. g., shock-boundary layer interactions, high dynamic pressures) and cumulative material damage.

(3) Structural integration of CMC hot components, where thermal protection and load-bearing functions are combined, producing complex interface behaviors.

This section will conduct an in-depth analysis of these three core challenges, clarifying their physical nature. The potential impact mechanisms of these challenges on the structural flutter boundaries of advanced engine CMCs will also be explored here.

1.1 Extreme aerodynamic heating and material performance evolution

The aerothermal environment has emerged as the primary external factor governing the stability of hot section structures. Due to the intense conversion of kinetic energy into thermal energy between high-speed airflow and component surfaces, critical engine parts, such as internal walls and turbine blades, are continuously subjected to high-enthalpy and high heat-flux operating conditions, exhibiting pronounced extreme aerothermal heating effects. Typical heat fluxes on engine channel walls can reach 1—5 MW/m^2, while local regions such as the combustor trailing edge and turbine vanes may experience values exceeding 10 MW/m^2, significantly surpassing those found in conventional jet engines. Furthermore, the thermal environment along the wall surface shows steep gradients both in the flow direction and through the wall thickness, leading to localized thermal stress concentrations, non-uniform thermal expansion, and thermal mismatch at interfaces[21]. In addition, rapid engine startups and transient operating conditions result in abrupt thermal transitions, where materials are subjected to high-temperature loading before reaching thermal equilibrium, giving rise to prominent thermo-mechanical transient coupling behaviors. The multi-physics interactions in CMCs hot structures are summarized in Fig.3[12].

Shock waves and boundary layer disturbances often overlap with high-temperature hot zones, making it difficult to stabilize and control the thermal environment[22]. The thermal environment (subjected to high-temperature loads) undergoes sudden changes while the material has not yet reached thermal equilibrium, thus exhibiting significant thermal lag

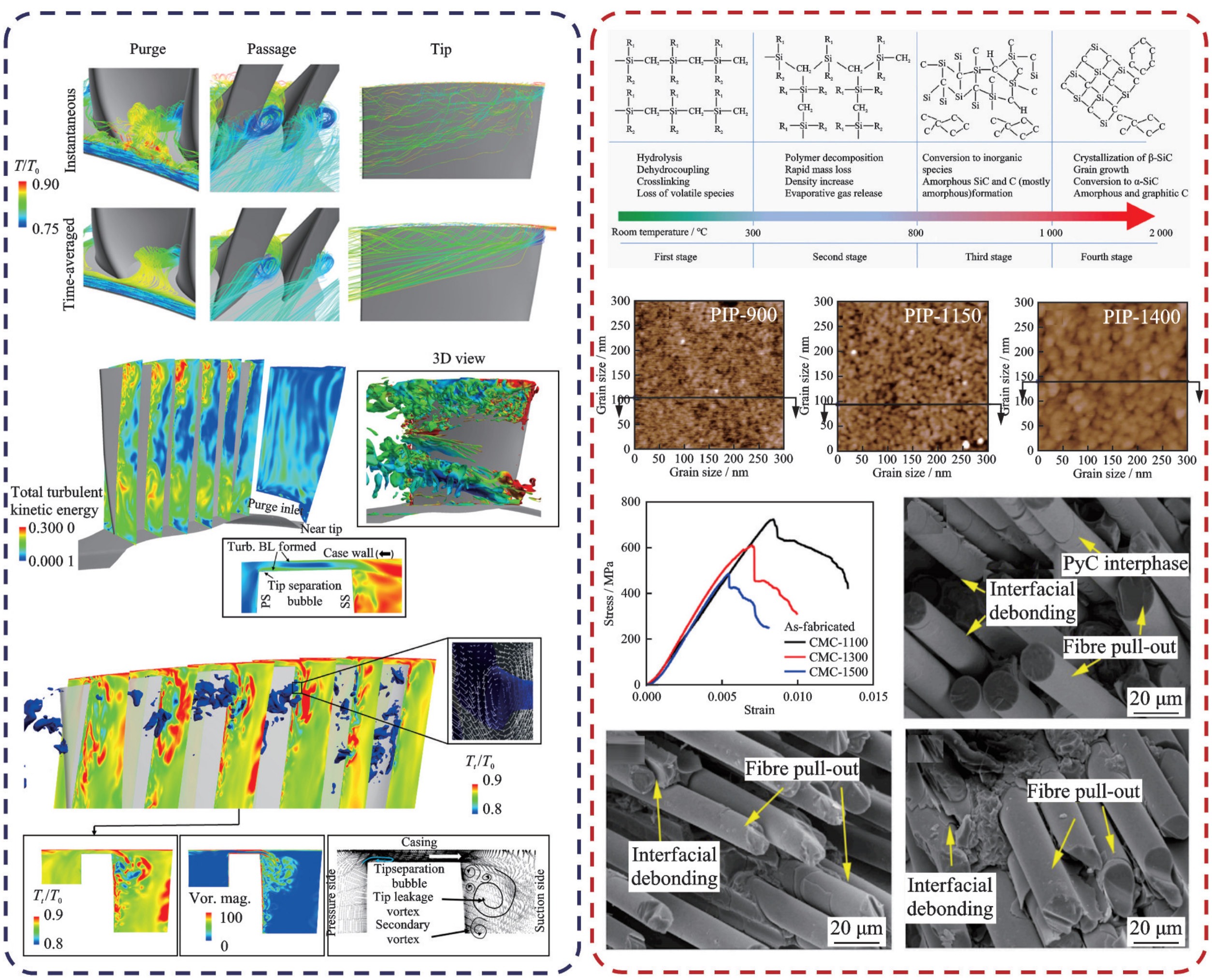

Fig.3 Extreme aerodynamic heating and material performance evolution[12]

and transient thermal-mechanical coupling response behaviors, especially during startup or variable operating conditions. At the same time, shock-wave-boundary layer coupling and pressure difference factors also enhance the spatial complexity of the thermal environment. In the CMC material system, this extreme aerodynamic heating not only drives macroscopic thermal load responses but also significantly alters the temperature field distribution, thermal expansion behavior, and thermal stress state, thereby affecting the modal characteristics and flutter boundaries of the structure[23]. Wu et al.[24] pointed out that in high temperatures, SiC fibers exhibit phenomena such as grain growth, matrix crystal phase reconstruction, and interface degradation, leading to the dynamic evolution of material mechanical parameters. Chen et al.[21] indicated that oxygen diffusion plays a dominant role in interface degradation via the oxygen atmosphere-biased linear oxidation model, thereby causing a significant reduction in the effective stiffness of the material. Kawai et al.[25] used finite element analysis (FEM) and interface fracture tests to study the initiation and propagation criteria of interface cracks in the environment barrier coating (EBC). He also proposed a design scheme to optimize the coating thickness to improve mechanical reliability. Under the combined effect of high-temperature creep and oxidation, the overall stiffness of the structure decreases, the damping characteristics change, resulting in reduced flutter margin, and even the activation of new unstable modes (such as shear buckling mode) and the occurrence of delayed flutter phenomena. Therefore, accurately characterizing the interaction laws between the thermal environment and the nonlinear evolution of material properties is crucial for establishing a high-fidelity vibration stability analysis model. All studies from the microscopic interface damage evolution, thermal-force coupling response to the macroscopic dynamic modulation highlight the profound influence of extreme aerodynamic heating on the flutter characteristics of CMC hot structures.

1.2 Coupling of high dynamic pressure, severe unsteady aerodynamic forces and damage

The internal flow of the engine exhibits significant non-stationary characteristics, especially at the inlet-isolator transition, the combustor entrance, and the nozzle throat region. These areas are generally located in a complex flow environment with high dynamic pressure and non-stationary aerodynamic forces coupled together. Shock waves, shear layers, wake structures, and flow instabilities can trigger broadband, high-energy pressure pulsations, which include both low-frequency sub-modal components and high-frequency higher-order modal components[26-27]. Some of these frequencies may overlap with the inherent modal intervals of the structure, resulting in significant modal excitation risks. Fig.4 shows the coupling mechanism between high dynamic pressure, strong unsteady aerodynamic forces, and structural damage[26-27].

Compared to subsonic conditions, the aerodynamic amplitude under high dynamic pressure conditions is greater, and the speed is faster, forming transient impact-like excitation. The engine is also often accompanied by shock-boundary layer interference, wake interaction, and flow separation/reattachment phenomena, causing the time-domain waveform of the aerodynamic force to significantly deviate from the harmonic form and exhibit non-stationary and non-periodic characteristics. High-frequency aerodynamic excitation is usually concentrated in regions with high shear rates and high heat flux, strongly coupled with the high-temperature thermal stress zone, further complicating the modal response behavior.

These complex non-stationary aerodynamic forces serve as external driving sources for structural vibration and material damage, featuring multi-spectrum, multi-scale, and uncertainty characteristics. They may lead to enhanced transient responses, intensified modal coupling, and even superimposed resonances with initial material defects in local hotspots, accelerating fatigue damage and interface degradation. Jagodzińska et al.[28] studied the flow through a linear turbine cascade (VKI LS-59 blades) under high-subsonic and transonic conditions. The results show that, in the transonic case, a shock forms and interacts with the boundary layer and the trailing-edge wake, leading to stronger un-

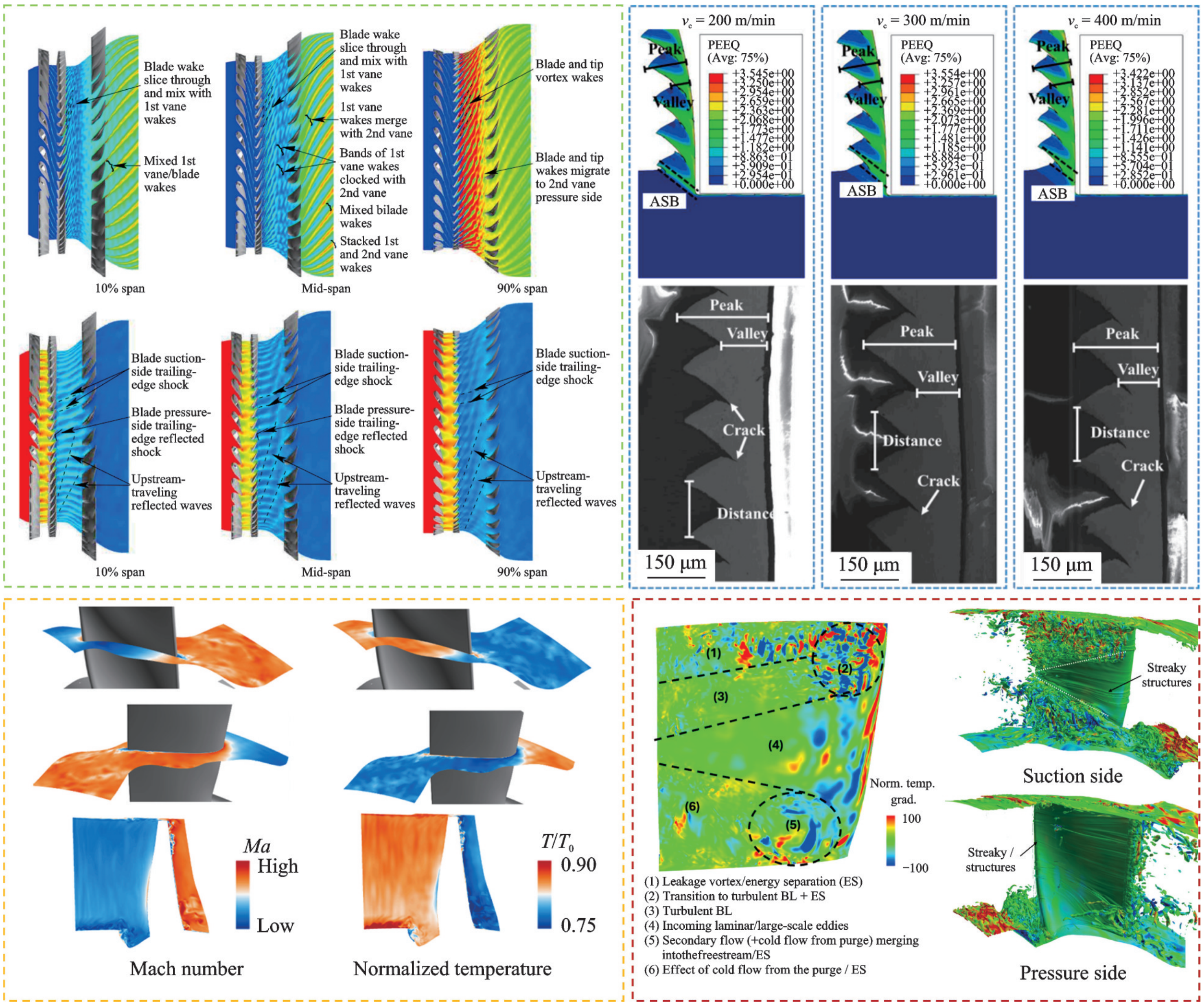

Fig.4 Coupling of high dynamic pressure, strong unsteady aerodynamic forces, and damage[26-27]

steady flow features at the cascade exit compared with the subsonic case, as evidenced by surface pressure, particle image velocimetry (PIV) and Schlieren measurements. Wang et al.[29] carried out a transonic compressor simulation. It revealed that unstable flow in the tip clearance region (such as tornado-like structures) can induce rotational instability (NSV). It also showed that the vibration amplitude of the blades increases the fatigue risk. Brandstetter et al.[30] further pointed out that circumferential flow disturbances can have a "locking" effect with the blade's inherent frequency mode, directly modulating the structural modal characteristics. Moreover, existing studies have shown that such aerodynamic instabilities can lead to strong vibrations that may cause high-cycle fatigue failure[31].

Therefore, although the non-stationary aerodynamic characteristics do not directly determine the material damage mechanism, they provide an excitation path and energy input for material performance evolution. In the modeling of CMC hot structures, the time distribution, spectral content, and source characteristics of unsteady loads must be explicitly included to enhance the accuracy of flutter boundary prediction and damage evolution assessment.

1.3 Challenges and design of CMC hot structures in extreme hot environments

As aero-propulsion systems evolve toward extremely high heat flux densities and operating temperatures, the conventional design approach of separating thermal protection layers from structural supports has become inadequate for future engines. In contrast to TPS used in vehicle-level applications, CMC hot structures in engines integrate thermal protection and load-bearing functions within a single component. They have gradually become the core design form for critical hot-section parts such as combustor liners, nozzle throats, trailing edges, and turbine guide vanes in advanced propulsion systems. This type of structure possesses advantages such as lightweight, high strength, and integrated thermal-structural integration, but it introduces significant complexity in design and analysis. The differences in thermal expansion coefficients, thermal conductivity, and mechanical properties among the multiple layers of the multi-layer composite configuration make the interfaces prone to high thermal stress concentration, delamination, and microcracks under thermal shock or gradient temperature fields. Compared to traditional structures that only bear mechanical loads, CMC hot structures have to endure high-temperature thermal loads, aerodynamic, as well as centrifugal forces at the same time. It results in the strong geometric nonlinear deformation, thermal buckling, and thermal creep reconfiguration. In addition, it also leads to a significant narrowing of the design space for stiffness, stability, and thermal isolation performance[32]. The coupling behavior spans from the microscale of the material to the overall structural scale. The structure typically consists of a bearing layer, a thermal insulation layer, and an oxidation-resistant coating. The responses of the braided layer, interface layer, and the overall component are coupled, and the cross-action of thermal, load, and vibration makes the modeling scale range large and the solution complexity high[33]. The current performance evaluation system mostly relies on empirical formulas and safety margin design, lacking a unified quantitative framework to analyze the attenuation of thermal protection capability, life degradation, and fatigue responses under dynamic loads.

Studies have shown that the interaction between shock waves and boundary layers can amplify unsteady heat flows and change the flutter boundary. When the local heat flux density is excessively high, the fine-scale stress concentration arising from the mismatch in thermal expansion between the matrix and the fibres influences the macroscopic stiffness distribution through multi-scale pathways. In combination with aerodynamic shock-wave excitation, this effect further reduces the flutter margin[33].

Therefore, the multi-functional synergy and thermal-structural-aerodynamic multi-field coupling modeling must be taken into account while designing CMC hot structures to achieve cross-scale response prediction. This not only poses challenges to traditional structural analysis methods but also provides necessary inputs for material constitutive and failure mechanism modeling. Developing efficient multi-field coupled numerical analysis methods and interface/coating optimization design will be the key research directions for improving their service performance and stability.

2 Nonlinearity, Inhomogeneity and Anisotropy of CMCs

It marks a significant leap by replacing traditional metallic materials with CMCs as the aero-engine hot structure material. Their unique composition and multiscale architecture intrinsically couple mechanical behavior and damage evolution with external multiphysics fields. This coupling, particularly under harsh high-temperature, high-pressure conditions, dramatically amplifies the inherent anisotropy, heterogeneity, and nonlinearity of CMCs, profoundly affecting structural vibration stability and flutter characteristics.

Despite these inherent strengths and design considerations, the operational environment introduces significant challenges. Concurrently, elevated temperatures severely degrade the critical toughening mechanism of fiber bridging through interfacial oxidation and property deterioration, accelerating unstable crack propagation and compromising structural integrity. Manufacturing-induced defects (pores/microcracks) evolve into damage initiation sites during high-temperature operation, exhibiting strong coupling with interfacial behavior that intensifies failure complexity. Consequently, developing advanced constitutive models capable of accurately capturing these multiscale, multifield coupling phenomena is important for achieving high-fidelity safety assessment of engine hot section structures.

2.1 Hierarchical structural coupling

At the microscale, the basic units composed of fibers, matrix, and interface phases are the core basis for damage initiation. Fig.5 illustrates the microscale structure and coupling modelling of hierarchical structure. Among them, fibers, as the main load-bearing phase, provide strength and stiffness, while the matrix is responsible for load transfer. Interface phases (such as pyrolytic carbon and boron nitride) influence material toughness by controlling

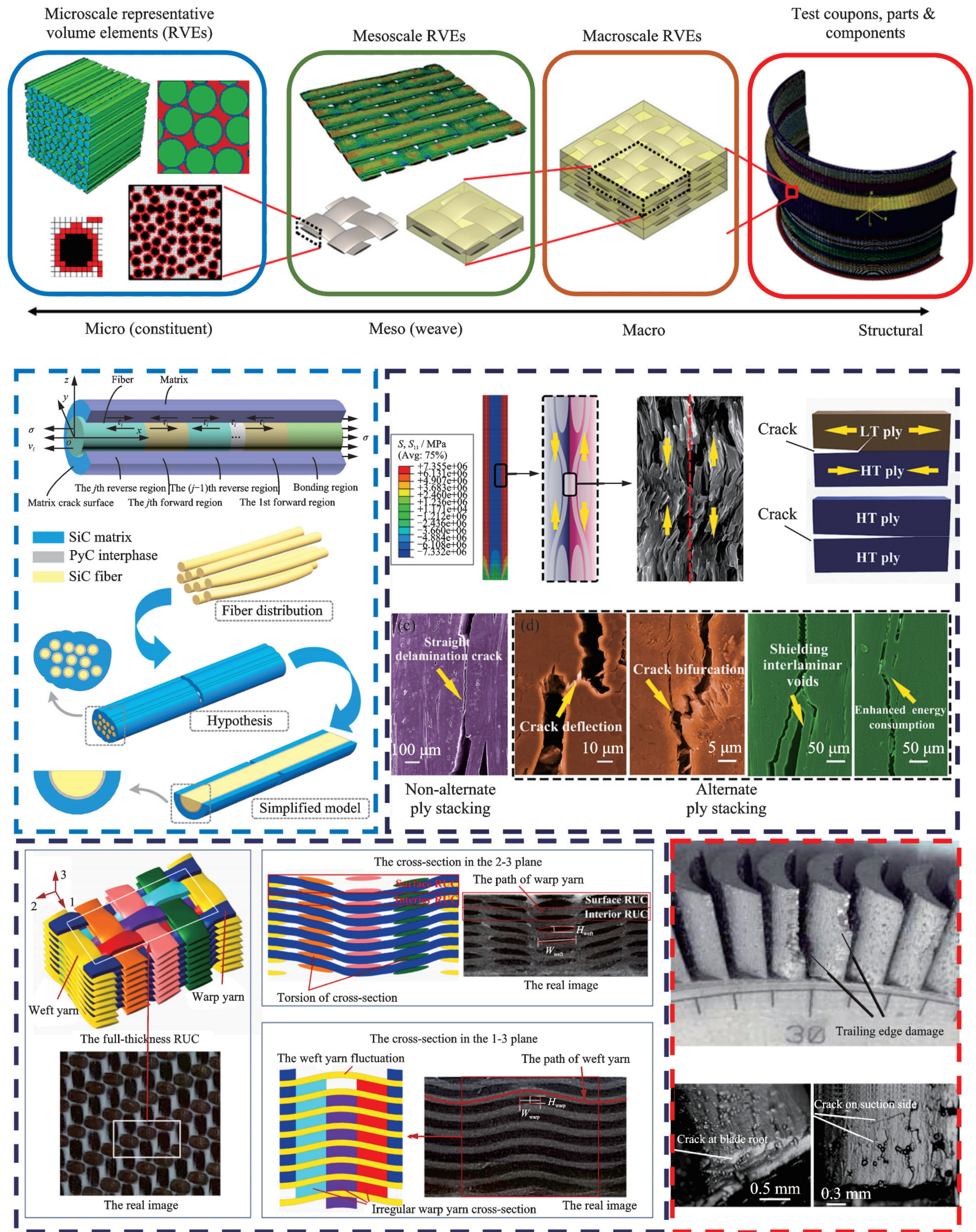

Fig.5 Microscale structure and coupling modelling of hierarchical structure[34]

crack propagation paths and energy dissipation mechanisms[34]. However, at high temperatures ranging from 1 200 ℃ to 1 500 ℃, the thermal decomposition, oxidation, or chemical reactions of interface phases can lead to a decline in bonding strength and frictional properties, making microcracks more prone to propagate along the interface. The nonlinear hysteretic characteristics of interface slip directly affect dynamic stiffness and damping responses. Xu et al.[35] proposed an anisotropic finite element model by introducing interface constraints to accurately predict the evolution of microcracks and interlaminar delamination. Baier et al.[36] optimized the microstructure through the reaction melt infiltration (RMI) method, confirming the regulatory effect of microstructural modification on mechanical properties.

The mesoscale, as a key link between the microscale and macroscale, influences damage propagation through the fiber weaving configuration (two-dimensional or three-dimensional) and matrix porosity characteristics by regulating the local stress field. CMCs are typically formed through chemical vapor infiltration (CVI) or polymer infiltration pyrolysis (PIP) processes. The arrangement of fiber bundles, weaving angles, and matrix infiltration quality directly determines the local stress redistribution. For instance, at 1 000 ℃, the in-plane shear stiffness of two-dimensional woven structures is significantly lower than that of three-dimensional woven structures, and stress concentration between bundles can easily become the initiation zone for cracks[8,37]. Rossol et al.[38] studied the mesoscale behavior of woven C/SiC composites using image-based finite element modeling, and showed that the fiber weaving architecture (2D/3D), tow arrangement, and matrix porosity significantly regulate the local stress field, thereby influencing the initiation and propagation of damage from defects and voids along tow-matrix interfaces. Yu et al.[39] found that the pyrolysis temperature of electrospun SiC_f/SiC can simultaneously optimize mechanical and electromagnetic properties by regulating mesoscale interface characteristics.

At the macroscale, as the ultimate manifestation of CMCs in service, the geometry, layup design, and boundary conditions of components integrate micro and mesoscale behaviors to determine the overall response. The layup sequence, angles, and fiber volume fraction affect the macroscopic stiffness anisotropy, while edge constraints and connection forms may induce local stress concentration. Sadowski et al.[40] proposed a unified multiscale model to clarify this phenomenon. Li[41] introduced the concept of "effective fiber volume fraction in the loading direction", which clearly demonstrated the influence of different preforms (unidirectional, 2D/3D woven, etc.) on hysteretic behavior and life. The attenuation of modal stiffness and frequency shift in high-temperature vibration tests directly reflects the cascading transfer of microcracks and mesoscale pores to macroscopic responses.

In summary, the performance evolution of CMCs is the result of the coupling of microscale interface evolution, mesoscale structural response, and macroscale configuration. This multi-level coupling becomes more complex in extreme aerothermal environments, directly related to the vibration stability and flutter boundary of hot-end structures. Therefore, establishing a cross-scale coupling model to accurately capture the "micro-mesoscale-macroscale" information transfer mechanism is a core prerequisite for improving the prediction accuracy of CMC service performance.

2.2 Nonlinear constitutive coupling

Based on the multi-level structure coupling, the mechanical response of CMCs under high-temperature complex loads exhibits significant multi-physical mechanism coupling characteristics, specifically manifested as the interweaving of nonlinear damage evolution and hysteretic energy dissipation behavior. This complexity stems from the synergistic effect of multi-scale structures from micro to macro under multi-field conditions, such as thermal, mechanical, and loading rate, which affects the load transfer path and damage propagation mode.

Under extreme conditions at the hot end of engines, the stress-strain curves of CMCs are generally highly nonlinear, which is not caused by a single mechanism but rather the combined effect of thermal softening, damage evolution, strain rate sensitivity, and interface frictional dissipation[42]. Under typical tensile/bending loads, their responses can be divided into four stages: (1) The initial linear elastic stage, where micro-defects have not yet expanded; (2) the matrix cracking stage, where cracks initiate in the matrix-rich area and propagate along the main tensile direction after the stress exceeds the threshold, resulting in a significant decrease in stiffness and the formation of a softening zone; (3) the crack saturation stage, where bridging fibers become the main load carriers and stiffness tends to stabilize; (4) the fiber fracture stage, where overall failure occurs. This process reflects the sequential activation of multi-scale damage mechanisms, and the stiffness degradation is usually characterized by introducing an internal damage variable based on strain history within the framework of continuum damage mechanics (CDM)[43]. Fig.6 illustrates the nonlinear constitutive model and damage mechanism[44-46].

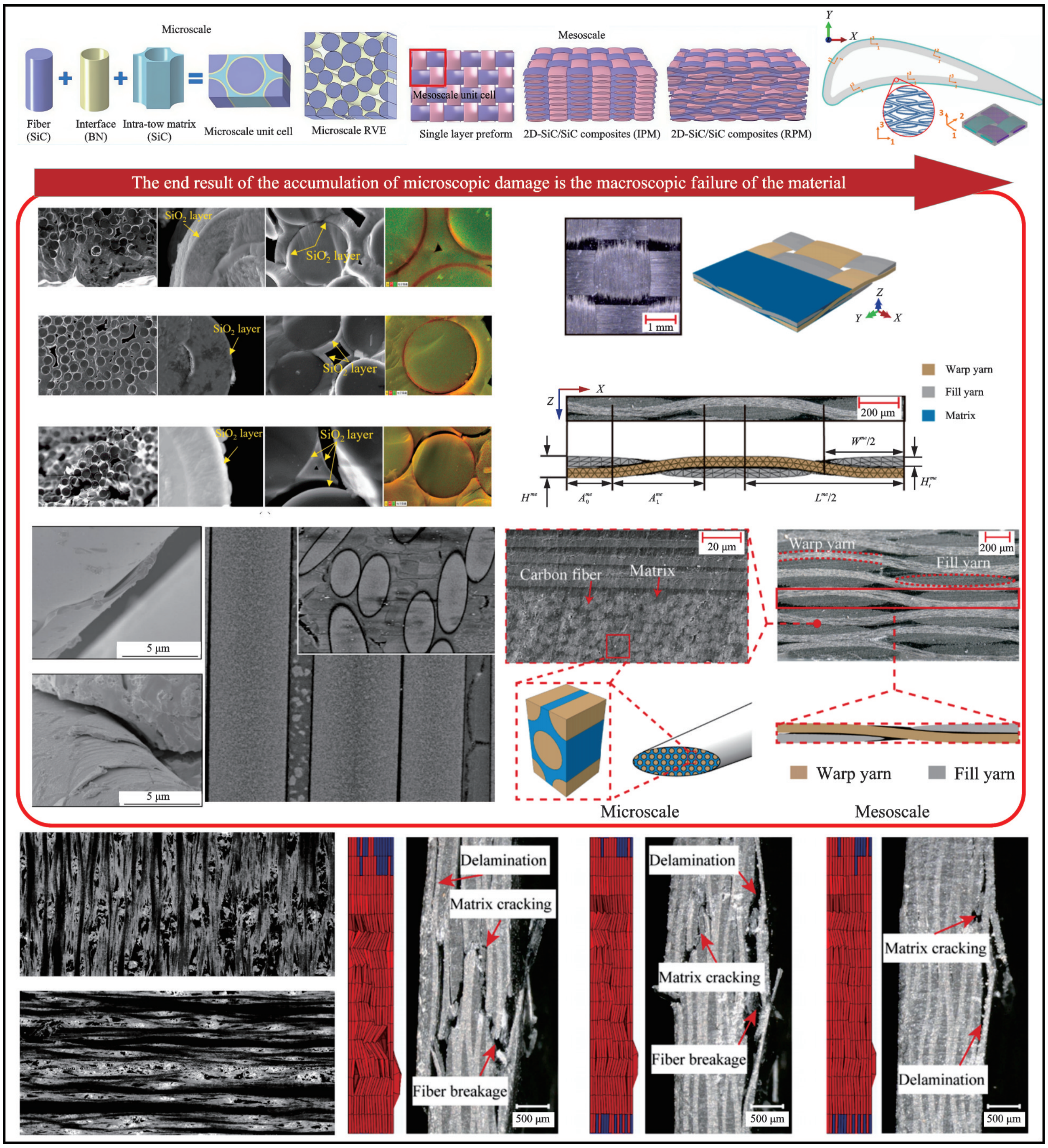

Fig.6 Nonlinear constitutive model and damage mechanism[44-46]

CMCs are also highly sensitive to strain rate and temperature: Materials such as SiC/SiC exhibit rate hardening effects (elastic modulus, yield strength, and ultimate strength increase with strain rate) over a wide strain rate range, but the fracture strain may decrease. Therefore, the constitutive model needs to incorporate temperature and strain rate-related parameters. Under cyclic thermal-mechanical loading, CMCs also show asymmetric hysteretic loops, which are attributed to interface sliding, crack opening and closing, and frictional dissipation. The interface not only transfers loads but also regulates dynamic responses through frictional energy dissipation. Interface degradation caused by high-temperature oxidation and pyrolysis further alters the hysteretic behavior, affecting the dynamic stiffness and stability of the structure. Therefore, accurately quantifying the damage-damping coupling relationship is crucial for predicting the response amplitude and flutter stability under dynamic excitation. The high-order constitutive models need to explicitly consider such coupling terms.

Existing research provides rich support for the above understanding. Jollivet et al.[47] pointed out that damage rapidly accumulates within 20% of the life of the composite material, and stiffness reduction can be used as an evolution criterion, revealing the sequence of interface and matrix cracking. Li et al.[48] found two fracture modes determined by microstructure in split hopkinson pressure bar (SHPB) compression tests at different temperatures, one of which can increase toughness by 35% without reducing strength. Wang et al.[49] established a multiple failure mechanisms-based damage model for 2D SiCf/SiC composites and combined it with an XGBoost machine learning algorithm to predict the failure envelope under complex loading conditions. The model captures nonlinear mechanical behavior caused by microstructural features and links mesoscopic information to macroscopic failure responses. Jindal et al.[50] developed a probabilistic damage modeling framework and thermal shock risk assessment for an ultra-high temperature ceramic matrix composite thruster. Shen et al.[34] introduced controllable residual thermal stress (RTS) by laying fiber layers with different thermal expansion coefficients, inducing crack bifurcation and deflection, and increasing the bending strength by 66% and the Weibull modulus from 4.9 to 8.3. Ceglie et al.[51] found that even in the absence of friction, geometric and material nonlinearity can cause path-dependent energy dissipation. In summary, the complex nonlinear constitutive behavior of CMCs in the engine service environment is a macroscopic manifestation of the coupling of multiple physical mechanisms. In aeroelastic analysis and life prediction, the use of advanced constitutive models that can reflect the coupling of damage and damping, temperature and strain rate dependence, and multi-scale damage evolution characteristics is a prerequisite for obtaining reliable predictions, and also provides a theoretical basis and methodological support for engineering design under extreme service conditions.

2.3 Tension-compression asymmetry

CMCs exhibit significant mechanical behavior asymmetry under tensile and compressive loads, as shown in Fig.7[52]. This characteristic profoundly affects the aerodynamic elastic stability of the structure and is a crucial factor that cannot be ignored in response analysis under extreme conditions. For two-dimensional woven or laminated structures, this asymmetry is not only reflected in the differences in stress-strain curve morphology, stiffness evolution path, and failure mode, but also accelerates performance degradation through cumulative damage and interface slip in cyclic thermal-hydraulic loads, thereby continuously influencing the flutter boundary and stability margin.

Under monotonic tensile loading, the damage mechanism mainly consists of matrix cracking, crack deflection, and fiber bridging: Cracks mostly extend perpendicularly to the load direction, deflect or stagnate when encountering reinforcing fibers, dissipate energy through interface slip and fiber pull-out, and exhibit "pseudo-plastic fracture" behavior, characterized by early stiffness stability, mid-stage nonlinear softening, and final fiber fracture-dominated stiffness collapse.

In contrast, the compressive response is more complex, and the strength is significantly reduced. Initial microcracks and pore closure can temporarily increase the linear elastic stiffness, but as the load

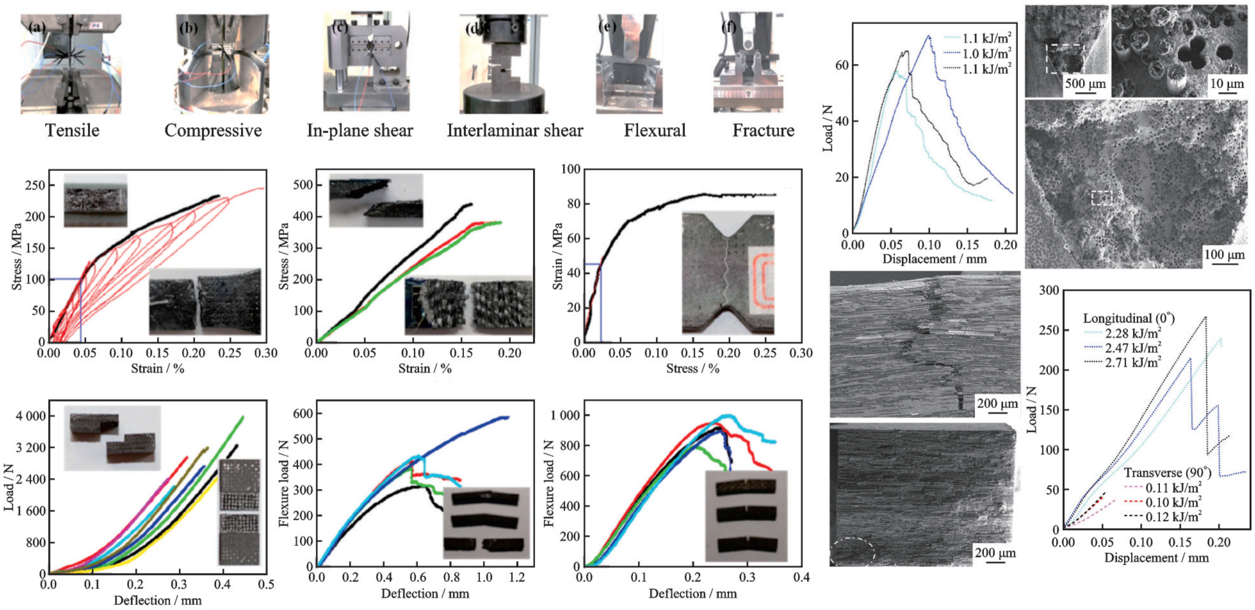

Fig.7 Tension-compression asymmetry phenomenon[52]

increases, multiple-mode superimposed failures such as fiber buckling, matrix shear failure, interface debonding, interlayer delamination, and macroscopic splitting occur. Even if the cyclic compressive stress is below the ultimate strength, irreversible damage and permanent deformation may still be triggered due to interface slip and microcrack connection. The cyclic fatigue experiment by Opalski et al.[53] shows that the strain amplitude of the compression segment in the hysteresis loop is significantly higher than that of the tensile segment, revealing the dominant role of compression in fatigue energy dissipation and interface degradation. The further cyclic fatigue experiment reveals that the strain amplitude of the compression stage in the stress-strain hysteresis loop is significantly higher than that of the tensile end, indicating that compression dominates the energy dissipation and interface degradation path of the fatigue process, which is closely related to mechanisms such as enhanced interface friction coefficient at high temperatures and stress concentration transfer in the matrix. Many studies provide multi-scale validation of the tension-compression asymmetry. Santhosh et al.[54] established a multi-axis damage constitutive model by coupling shear and normal damage, revealing the contribution of different loading directions to the nonlinear response, and can accurately capture the differences in damage evolution under tension and compression. The parametric FEM by Zhu et al.[55] indicates that the compressive failure mode of three-dimensional four-direction woven composite materials is highly correlated with the weaving angle, fiber volume fraction, and loading direction.

Under the combined effect of high temperature and cyclic loading, the asymmetry between tension and compression becomes even more pronounced. Azeez et al.[56] introduced crack closure effect and path-specific internal variables into the thermal coupling damage model, successfully depicting the segmented degradation of tension-compression stiffness at high temperatures. Birman et al.[57] confirmed that the increase in the compression ratio in cross-ply structures significantly increases crack density and hysteresis loop area.

The tension-compression asymmetry poses strict requirements for aerodynamic elastic modeling. If the assumption of tension-compression symmetric constitutive relationship is made, it will inevitably underestimate the stiffness decay in the compression zone, ignore the influence of hysteresis evolution on modal frequency and damping characteristics, and thus misjudge the natural frequency, flutter boundary, and fatigue life of the structure. Therefore, a high-fidelity constitutive model should explicitly introduce the mechanism of tension-compression path distinction, including differentiated damage evolution functions, directional friction of interface slip, and crack closure-opening behavior. At the same time, the influence of temperature on the interfacial bonding force, friction coefficient, and creep-fatigue interaction should be considered to enhance the physical transparency and engineering adaptability of the model. The asymmetric tension-compression behavior of CMCs stems from the fundamental differences in the microscopic damage mode and stress transfer path, and is significantly amplified under cyclic loading and extreme environments. This characteristic is directly related to the aerodynamic elastic stability and life assessment of the hot-end components. Accurately describing and modeling this behavior is the foundation for achieving high-precision analysis of key engine structures and optimizing material design.

2.4 Thermal bridging and crack propagation

The fiber bridging mechanism, as the core toughening path of CMCs, is subject to multiple coupling regulations from the temperature field, oxidation reactions, and interface evolution, and significantly differs from the behavior characteristics under room temperature conditions. When the matrix cracks, the reinforcing fibers cross the crack surface to form a bridging zone, which bears the tensile force and dissipates the crack tip stress through interface friction, delaying crack propagation and enhancing the material's fracture toughness.

The influence of temperature on the fiber bridging behavior exhibits significant nonlinear characteristics. The thermal-thermal-oxidation coupling criterion proposed by Deng et al.[58] indicates that the bridging stress decays exponentially with temperature increase. Above 1 200 ℃, the thickening of the oxide film leads to a sudden drop in the interface shear strength by more than 60%, and the bridging mechanism shifts from "friction-slip" dominance to "brittle fracture" dominance. This transition is particularly evident in the continuous climb engine operating conditions. When the interface insulation phases such as PyC or BN are ablated, the crack propagation stable stage is significantly shortened, and the crack growth rate can reach 2—3 times that at room temperature. Experimental observations further reveal that the temperature rise reduces the interface friction coefficient, causing the crack opening displacement curve of the bridging zone to shift from a power-law type to a nearly linear type, which is a "pre-signature of bridging instability" and can be used as a key criterion for predicting the remaining life of the material.

To analyze the microscopic evolution process of the high-temperature bridging mechanism, using synchrotron in situ μCT and digital volume correlation (DVC), the damage evolution of woven SiC/SiC under high-temperature tensile is tracked in three dimensions, capturing the gradual/layer-by-layer fracture of the bridging fibers and their sequential interaction with the matrix crack network[59]. Meanwhile, it is observed that the redistribution of the stress field near the crack tip will trigger the generation of secondary cracks and exacerbate the complexity of the damage[60]. Similar in-situ layering and stress-redistribution-driven crack network expansion have been demonstrated in the literature, and the in-situ thermal layering method has also been shown to be feasible. This provides a basis for the numerical implementation of the dynamic bridging stress thermal attenuation function, the interface friction evolution model, and the tensile-closed crack displacement-load path. At approximately 1 200 ℃, the interface mechanism of SiC/SiC composite materials may shift from "fiber pull-out" to "fiber fracture", corresponding to a significant decrease in material strength[61].

Furthermore, Fan et al.[62] summarized the inversion data of bridging stress in the 800—1 500 ℃ range, providing rich empirical support for the construction of a high-temperature constitutive model. Brockman et al.[63] discovered the coupling law of bridging toughness with grain size and thermal expansion anisotropy, further expanding the application space of acoustic emission monitoring technology in online assessment of high-temperature fatigue. It is worth noting that the influence of temperature on the bridging mechanism is more complex under fatigue loading. The high-temperature environment significantly affects the bonding performance of the fiber/bulk interface, thereby accelerating the expansion process of fatigue delamination. Chen et al.[64] found in the SiC ceramic fatigue crack propagation experiment that when the temperature rises from room temperature to 850 ℃, the fatigue threshold decreases by approximately 28%, accompanied by a significant increase in the crack propagation rate, indicating that the increase in temperature significantly accelerates the crack propagation behavior. Therefore, to accurately assess the stability and durability of CMC structures, it is necessary to construct a high-fidelity bridging model that is temperature-dependent.

In conclusion, the fiber bridging behavior under high-temperature conditions is a dynamic process of coupling multiple factors such as temperature, mechanical load, and interface evolution. Existing research has formed a relatively complete technical chain from experimental observation, theoretical modeling to material design, but further challenges such as physical modeling of bridge failure at extreme temperatures (>1 600 ℃) and real-time coupling calculation of multi-scale damage evolution need to be addressed. In the future, by integrating artificial intelligence algorithms with in-situ monitoring technology, the development of a "temperature-oxidation-damage" closed-loop prediction model will be a key breakthrough direction for enhancing the reliability of high-temperature structures of CMCs.

2.5 Defect-initiated damage coupling

CMCs inevitably generate microstructural defects such as pores, initial microcracks and interface discontinuities during the preparation process (e.g. CVI, PIP), as shown in Fig.8[12]. Under the action of multiple physical fields such as thermal stress cycling, high-temperature oxidation and mechanical excitation, these defects are strongly coupled with the fiber/matrix interface damage, jointly controlling the initiation path, propagation rate and stiffness degradation of cracks, which is a key prerequisite for establishing reliable constitutive and life assessment methods.

The initial defects are the "seeds" for damage initiation, and their spatial statistical characteristics directly determine the stress concentration and failure initiation. Zhang et al.[65] observed in SiC_f/SiC dovetail joints that the actual pore distribution changed the spatial pattern of failure units, and delamination cracking became the dominant factor, with the ultimate strength decreasing by 15%—20% compared to the defect-free model. Under alternating thermal and mechanical loads, microcracks and pores can form random "weak links", significantly reducing the initial crack stress (with a reduction of up to 30%) and accelerating unstable expansion.

The fiber/matrix interface, as the most sensitive area, is the core medium for defect-damage coupling. For example, Alabdullah et al.[66] proposed a continuum damage model within a thermodynamic framework that captures the non-linear mechanical behavior of SiC/SiC ceramic matrix composites under combined radiation and thermal loading. Moreover, the increase in temperature alters the intrinsic properties of the matrix/interface and amplifies the thermal expansion mismatch, thereby enhancing the stress concentration at the defect site. Oxidation forms a positive feedback loop of "defect-oxidation-damage" through erosion of the interface phase and the surrounding matrix. The coupling under dynamic loads is more complex: 4D-XCT (X-ray computed tomography) in situ experiments captured the "jumping" expansion of the crack tip induced by micro-pore aggregation[67], while high-temperature XCT showed that interface slip and matrix cracking alternately dominated the crack tip behavior along the load path, resulting in a strong nonlinearity in the evolution[68]. In terms of data benchmarking, the 3D-XCT dataset system designed by Chen et al.[21] revealed the spatiotemporal coupling path of defect-interface-fiber fracture, providing a high-quality reference for detailed numerical and data-driven models.

In conclusion, the performance degradation of CMCs is jointly driven by the "defect-triggering-interface-guiding-multi-field amplification" chain: Initial defects determine the starting point of damage, interface deterioration determines the expansion path, and multi-field coupling amplifies and accelerates the evolution. Therefore, to construct a reliable constitutive model, it is necessary to explicitly consider the statistical distribution of defects, the evolution of interface strength, and the multi-field cou-

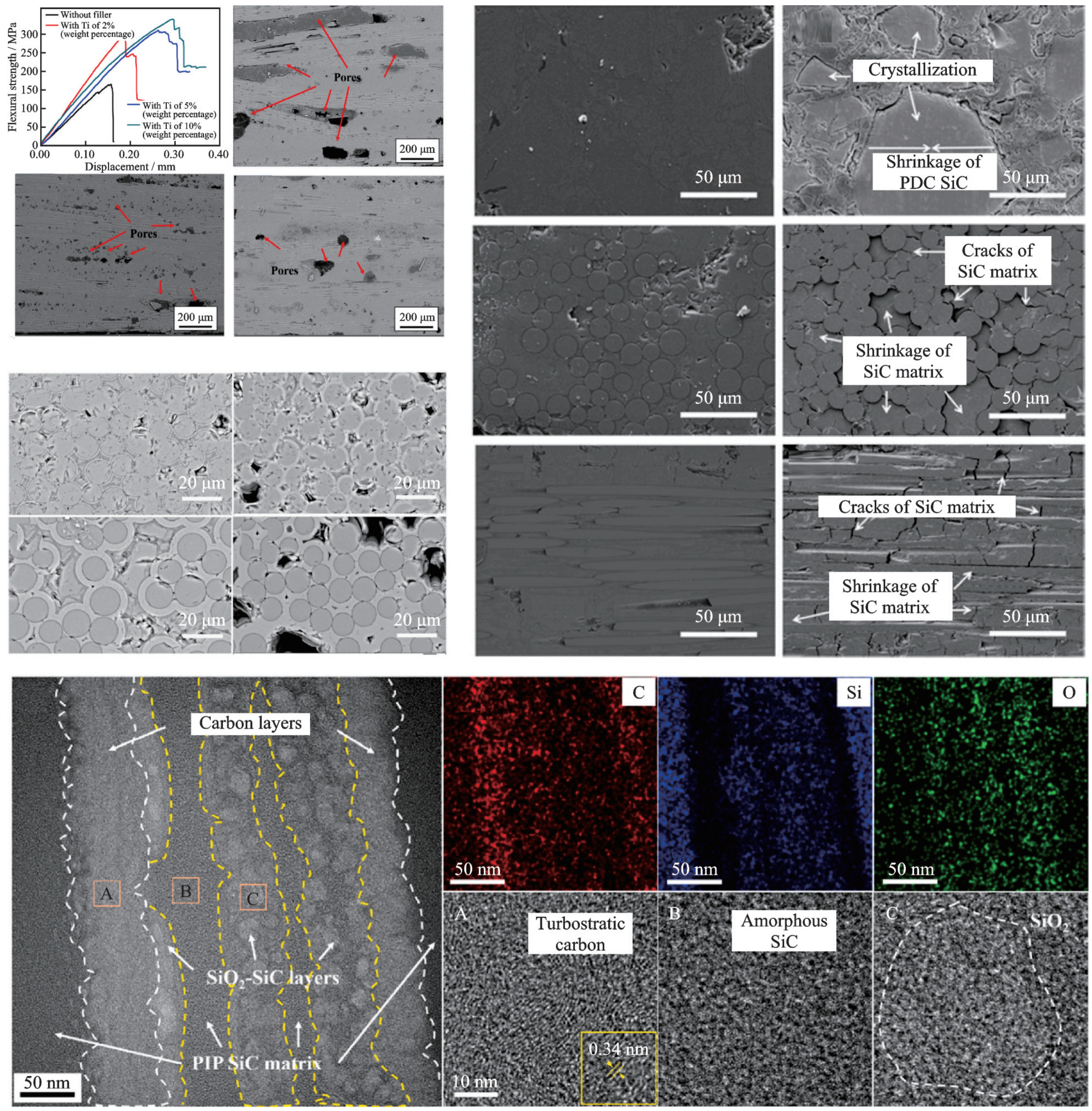

Fig.8 Defect-initiated microstructural damage[12]

pling effects of temperature-oxidation-crack propagation, and combine multi-source experiments calibration with data-driven modeling to provide a solid theoretical and methodological foundation for the structural safety assessment and design optimization of CMCs.

3 Multi-field Coupled Modeling and Analysis of CMC Hot Structures in Advanced Engines

Due to the complex multi-field coupling effects between extreme conditions (such as aerodynamic forces, extreme aerodynamic heating, explicit structural deformation, and the temperature-dependent nature of material properties) during hypersonic flight and damage evolution, traditional single-field independent or simplified analysis methods are unable to accurately capture the actual structural dynamic response and instability mechanism, and may lead to insufficient assessment of safety margins. Hence, it is urgent to develop advanced multi-field coupling modeling and analysis methods to accurately predict the aerodynamic-elastic response of hypersonic CMC structures. In recent years, researchers have developed various multi-field coupling analysis frameworks in this field, and have conducted extensive exploration on key issues such as aerodynamic-thermal-structural coupling, thermal-structural coupling, damage evolution coupling, multi-scale modeling, and coupled flutter analysis methods. This section will systematically review and evaluate the research progress of these cutting-edge modeling methods and analysis techniques.

3.1 Coupled analysis frameworks

The aerodynamic and elastic problems of hypersonic CMCs involve the coupling of multiple physical fields, such as the flow field, thermal field, structural field, and material nonlinearity and damage. Examples of the coupled analysis frameworks considering multi-physical fields were shown in Fig.9[15,34,69-70]. Moreover, due to the anisotropy of the materials, evolution characteristics of damage, and high-temperature sensitivity, the interaction of multiple fields exhibits high nonlinearity and time-varying characteristics. Traditional single-physical-field independent solution strategies are no longer sufficient to meet the requirements for precise prediction. The coupled analysis framework integrating the computational fluid dynamics (CFD), conjugate heat transfer (CHT), computational structural dynamics (CSD), and material damage behavior must be constructed to achieve collaborative simulation of multiple physical fields through synchronous or quasi-synchronous solution.

According to the degree of coupling, the analysis framework can be classified into two types: Loose coupling and tight coupling. The former solves the governing equations of each physical field independently and exchanges data, such as transferring aerodynamic forces to structural loads, feed-

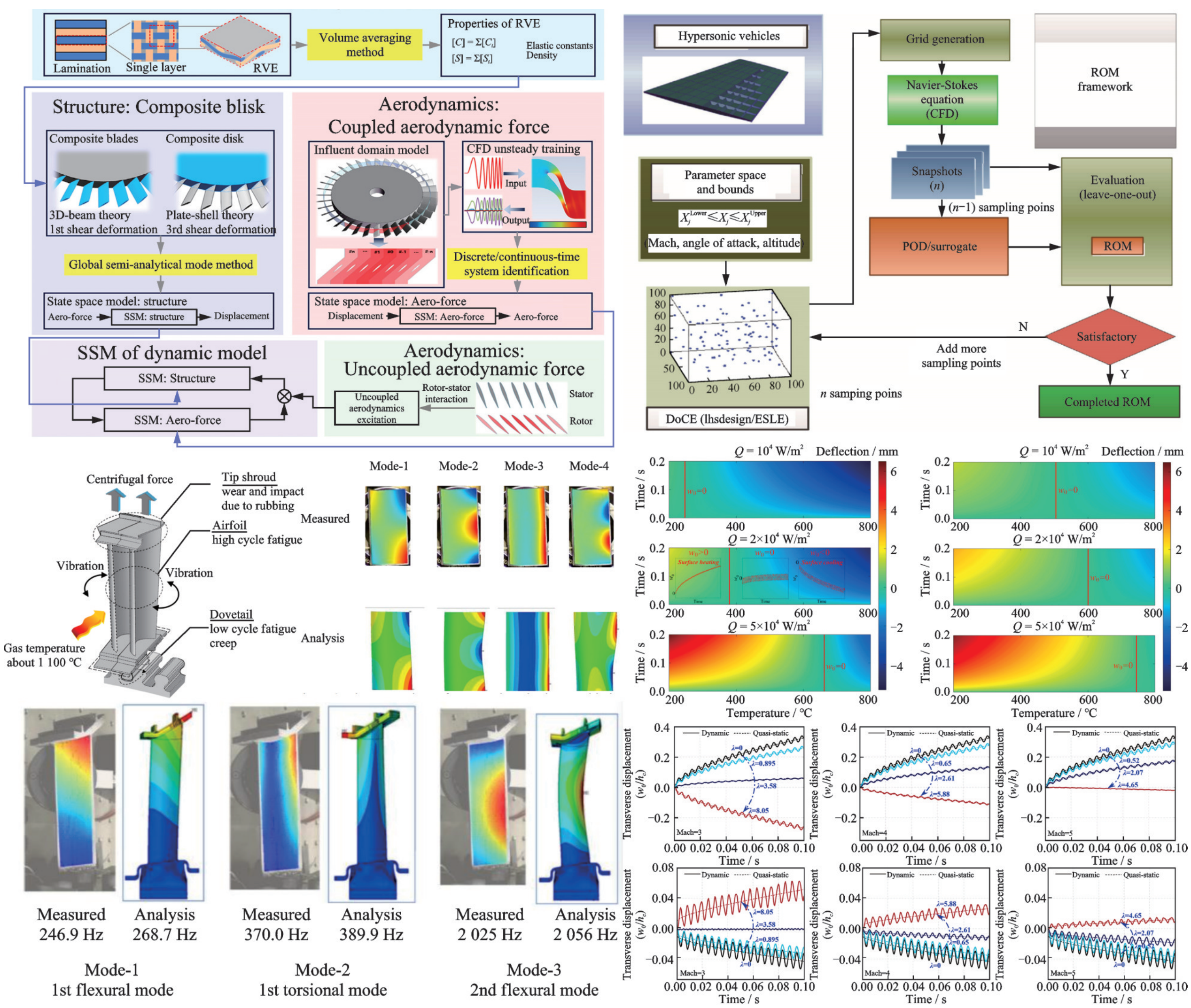

Fig.9 Coupled analysis frameworks considering multi-physical fields[15,34,69-70]

back structural deformation to the flow field boundary, and updating material performance parameters in the temperature field, within a predetermined time step or sub-iteration cycle to achieve inter-field coupling. Typical applications include the HyCCD partitioned coupling framework developed by Zhang et al.[71], which uses time-step adaptive interpolation to coordinate the data transfer of CFD-CHT-CSD, improving the stability and efficiency of thermal-structural coupling at hypersonic speeds. Cai et al.[72] proposed a novel iterative strategy of prediction-correction, which relaxes the time-step limit by dynamically adjusting the sub-iteration accuracy, more suitable for the transient response simulation of CMC thermal and mechanical dynamics. Wang et al.[73] predicted the thermal stress distribution of large energy pipelines using the fluid-solid-thermal loose coupling model, verifying the applicability of this framework in engineering-scale CMC structural analysis.

The loose coupling method can directly call mature commercial software (such as Fluent, Abaqus), with low implementation difficulty and ease of parallel computing, especially suitable for weak coupling scenarios, such as using the stiffness degradation results of the microscale damage model as the input for the structural field, simplifying multi-scale coupling through explicit data transfer. However, when dealing with strong coupling problems, such as local thermal-structural coupling caused by shock-wave-boundary layer interference, stability needs to be maintained by reducing the time step or densifying the sub-iterations, which significantly increases the computational cost, and the material nonlinear evolution is difficult to be reflected in the flow field in real time, leading to cumulative errors.

In contrast, the tight coupling framework integrates all physical field governing equations into a single nonlinear algebraic equation system and solves them synchronously through dedicated algorithms to eliminate field delays. For example, Joshi et al.[74] used the least squares finite element (LSFEM) to uniformly model the flow field, structural field, and pressure field, and combined numerical stabilization methods to significantly improve the stability of transient strong coupling problems. Rüth et al.[75] introduced AMP-Robin boundary conditions and quasi-Newton sub-iteration techniques to accelerate the convergence of fluid-solid interface data, making it suitable for the large deformation vibration of CMC blades. Matthies et al.[76] analyzed the influence of additional mass effects on the stability of coupling, and proposed a stability criterion across Biot numbers and Added-Mass numbers, providing theoretical support for the tight coupling analysis of thin-walled CMC components. This tightly coupled method boasts high accuracy and small coupling errors, enabling it to precisely capture the microscopic mechanisms of multi-field strength coupling. For instance, it can simultaneously solve the dynamic feedback of fluid flow heat flux, structural thermal deformation, and interface oxidation damage. It avoids the loose coupling of stepwise delay, in which fluid flow calculation is followed by temperature field transfer and subsequently by structural response. However, its solution algorithm is complex, the implementation cost is high, and the computing resource demand is large. Especially in the multi-scale simulation of three-dimensional woven CMCs, it limits the engineering application.

In general, the loose coupling framework is widely used in the current aerodynamic elastic analysis of CMC hot structure due to its flexibility and engineering adaptability. It is suitable for preliminary design and parametric research. While the strong coupling framework is more suitable for mechanism research and detailed analysis of key components due to its high-accuracy solution capability in strong coupling problems. In the future, a "loose-coupled-mixed strategy" can be developed based on the material characteristics of CMCs, using tight coupling in the strong coupling area, such as the leading-edge shock wave area, and loose coupling in the weak coupling area, i.e., the main flow area of the blade body, which was to balance accuracy and efficiency.

3.2 Modeling aero-thermo-structural coupling

Aerodynamic-thermal-structural coupling modeling is the core part of the aerodynamic elasticity analysis for the hot-end structure of hypersonic engine CMCs. Its accuracy directly affects the prediction of dynamic responses and flutter stability. The modeling process needs to cover aerodynamic and aerothermal calculations, structural thermal conduction and thermal deformation analysis, as well as the simultaneous solution of the flow-thermal-solid fields[77]. Aero-thermo-structural coupling analysis models were shown in Fig.10[77]. By considering the anisotropy, temperature dependence, and nonlinear damage evolution of CMCs, it aims to accurately simulate the multi-field interaction mechanism under extreme conditions. Phenomena such as shock waves, flow separation, and thermal chemical non-equilibrium in hypersonic flow fields make the prediction of surface unsteady pressure and heat flux extremely challenging.

To balance computational efficiency and accuracy at high Mach numbers, Ghaderi et al.[78] proposed a Bayesian surrogate model that integrates finite element data with uncertainty quantification, significantly reducing the computational cost associated with complex flowfield simulations. McNamara et al.[79] emphasized that at Mach numbers exceeding 6, thermo-chemical non-equilibrium causes more than 20% errors in aerothermal flow, directly affecting the evolution of interface oxidation and fiber bridging mechanisms.

The analysis of structural heat conduction and thermal deformation requires establishing a "microscopic-macroscopic" cross-scale correlation, breaking through the assumption of homogeneity and considering the regulation of the microstructure. Guo et

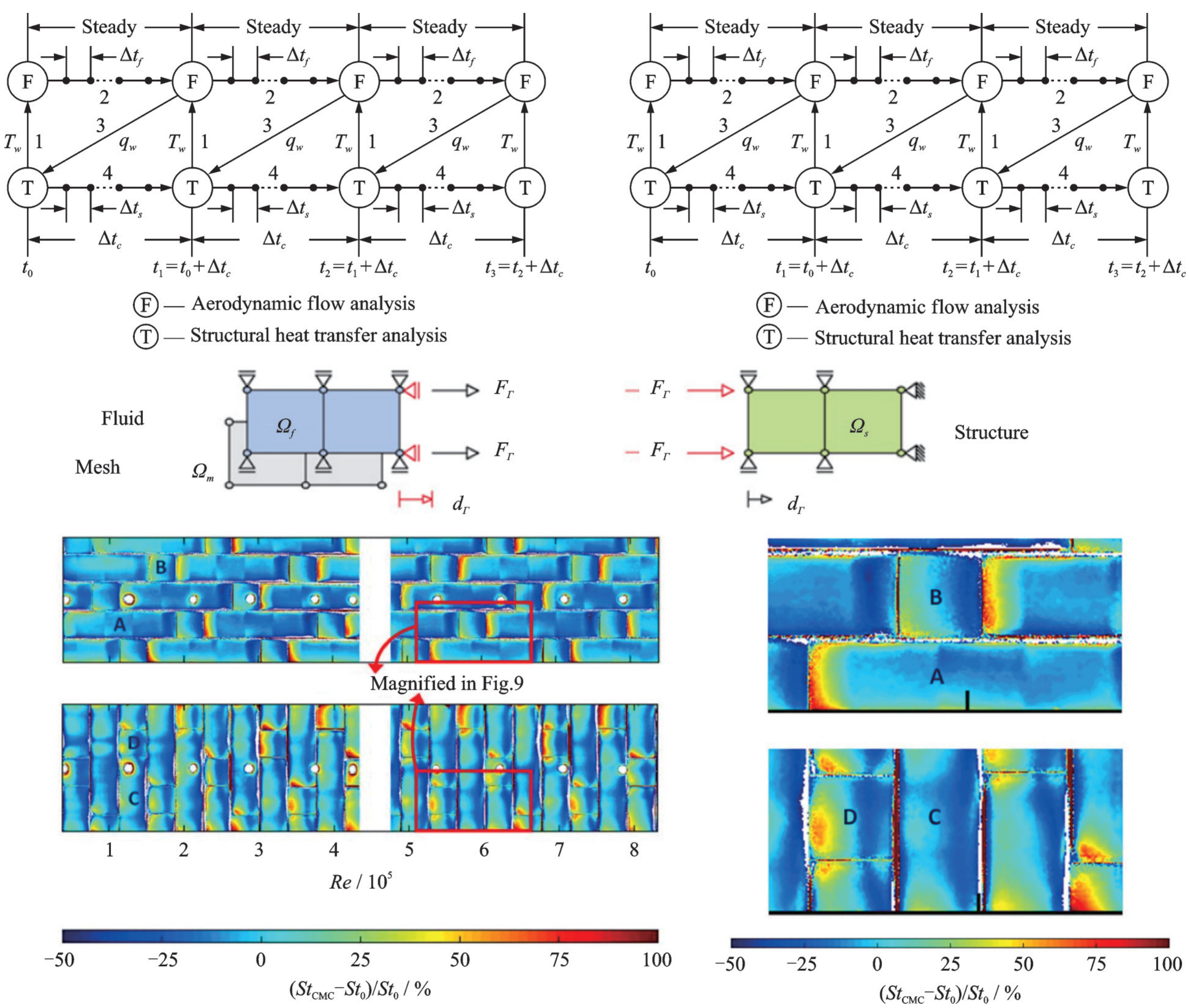

Fig.10 Aero-thermo-structural coupling analysis models[77]

al.[80] proposed a multi-scale thermal property model that reveals the significant influence of needle-punched fiber geometry on macroscopic thermal conductivity and contact pressure distribution, demonstrating that optimizing microscale parameters can effectively suppress thermal elastic instability. At temperatures above 1 800 ℃, Wan et al.[81] showed that the fiber/matrix thermal expansion mismatch can induce local thermal stress concentrations. Therefore, a microscale mechanical model needs to be employed for precise quantification, and the results should be applied to macroscopic structural analysis. Similarly, Zhao et al.[82] revealed the sensitive influence of interface defects and pores on thermal conductivity through three-level RVEs and homogenization theory, demonstrating that exceeding critical values in interface damage parameters can result in the reductions of 15%—20% in thermal conductivity, directly causing temperature field uniformity.

Effective aerodynamic-thermal-structural (ATS) coupling simulations must balance fidelity and computational efficiency. High-fidelity CFD-CHT-CSD frameworks are able to capture strong coupling phenomena such as shock-boundary layer interference and thermal-physical transient feedback, but at unaffordable computational costs. To address this challenge, Huang et al.[83] proposed a physics-informed reduced-order model based on POD-Galerkin expansion and dynamic error correction, compressing calculation times to 1% of the high-fidelity model while maintaining flutter boundary prediction errors below 5%. Moreover, Gao et al.[84] proposed a modal-driven M-RBF mesh deformation method, which can preserve interface mesh quality and load conservation with a minimum number of control points. In addition, Zastrow et al.[85] developed a data-driven operator inference-based model reduction framework for coupled aeroelastic flutter problems. Their reduced-order model reduced computation times by up to two orders of magnitude while maintaining high fidelity in flutter boundary predictions, providing an efficient solution for high-dimensional fluid-structure simulations.

Under specific thermal-hydraulic conditions, radiation conduction and cross-scale crack propagation also require tailored modeling approaches. Low et al.[86] demonstrated the significance of radiation conduction at high temperatures, accounting for over 40% of the total heat flux and necessitating joint modeling of phonon conduction and radiation transfer. Based on DEM-FEM coupling, Ghasemi et al.[87] revealed that both the crack density in ceramic coatings and increases in temperature synergistically accelerate interface debonding, indicating the necessity of incorporating a cross-scale crack propagation model into the coupling framework.

In summary, ATS coupling modeling is evolving towards explicit microscopic mechanisms, efficient macroscopic solution schemes, and integrated data-physics approaches. Progress is critically dependent on breakthroughs in real-time coupling algorithms for high-temperature nonlinear CMC damage, cross-scale thermal-hydraulic parameter transfer mechanisms, and dynamic reduction strategies applicable to large engineering components. These advances are essential to enabling safe design and life assessment of CMCs in hypersonic engine applications.

3.3 Modeling thermo-mechanical coupling

To simulate the dynamic interaction effects between the temperature field and the mechanical field, especially the nonlinear response of CMCs in extreme thermal environments, it is necessary to establish a temperature-dependent material property database, develop multi-scale constitutive models, and design efficient numerical algorithms[10,88-89]. Fig.11 illustrated the examples of thermo-mechanical coupling researches[90-92]. The mechanical performance parameters of CMCs, including elastic modulus, thermal expansion coefficient, and thermal conductivity, are highly sensitive to temperature. The elastic modulus of SiCf/SiC decreases by approximately 20% at 1 000 ℃, while the thermal expansion coefficient increases by 15%—20% above 800 ℃ due to interface oxidation. For instance, Wu et al.[10] carried out the gas-thermal-mechanical combined loading test indicates a 47.5% strength reduction for Cf/SiC at 1 500 ℃ compared to 1 000 ℃, while pre-loading can increase the strength by 38%. In-situ observation of surface strain fields at high

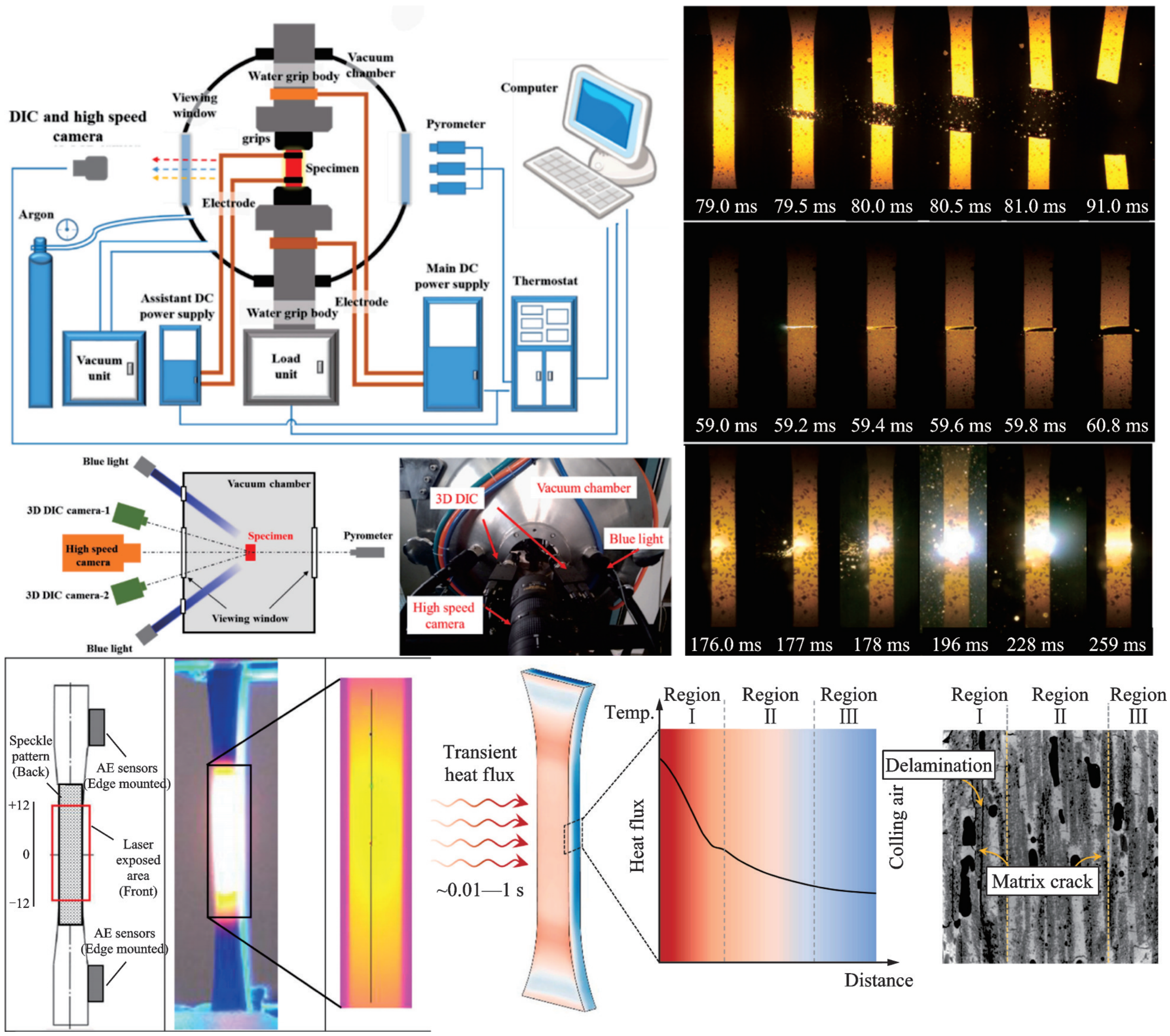

Fig.11 Examples of thermo-mechanical coupling researches[90-92]

temperatures, using techniques such as high-temperature DIC, as done by Mao et al.[88] on C_f/SiC at 1 300 ℃, reveals thermal expansion non-uniformities caused by interface debonding above 1 000 ℃.

Multi-scale constitutive models serve as the core of thermal-mechanical response modeling. A deep material network (FE-DMN) was proposed by Gajek et al.[93]. The computational efficiency by mapping local temperature-stress fields and microstructure damage bidirectionally was improved efficiency by 40%. Combining thermal-induced crack propagation with oxidation/creep softening, Sun et al.[94] developed a continuous damage model that fits the error within 6% across the temperature range of 25—1 500 ℃, ensuring long-term applicability for life prediction.

Efficient numerical algorithms are critical for implementing thermo-mechanical coupling within finite element analysis. Skinner et al.[95] updated element properties online through residual stress replay throughout the entire process, analyzing the brittle-ductile failure transition mechanism of C_f/SiC joints at 800 ℃. Combining fiber creep and matrix relaxation, Sullivan et al.[96] proposed the creep-thermal coupling model accurately predicts deformation over 500 h at 1 100 ℃/150 MPa.

Thermal-mechanical coupling is particularly challenging due to the synchronous superposition of non-uniform temperature fields and anisotropic thermal expansion. Specifically, high supersonic leading edges/hot section components will experience steep in-plane temperature gradients and strong unsteady heat flows due to aerodynamic heating, leading to significant thermal stress concentrations. The significant anisotropy of the CTE constitutive model of SiC_f/SiC and other woven CMCs, and the model's change with texture/volume fraction/pore evolution, will amplify mismatch stress and change the overall dynamic response in non-uniform temperature fields. Introducing functional gradient (FGM) transition layers/interfaces can significantly alleviate secondary stress caused by CTE mismatch and reduce the amplitude of thermal stress. Regarding dynamic characterization, it can be found that thermal-thermal synergy not only shifts frequencies but also changes damping through temperature-dependent energy dissipation mechanisms such as interface debonding/sliding and matrix cracking. For system-level assessment, high-fidelity multi-field coupling combined with reduced-order/data-driven approaches has been implemented[97]. The studies by Benavente et al.[98] and Takagaki et al.[99] revealed the deformation transfer mechanism during high-temperature creep and solidification processes.

To sum up, precise prediction of the strength, lifespan, and stability of CMCs under extreme environments relies on modeling the thermo-mechanical coupling, and using temperature-attribute databases, multi-scale constitutive laws, and efficient coupling algorithms. Developing real-time coupling closed-loop models, multi-physics extensions, and data-driven-physical fusion strategies are the focus of future efforts, designed to enhance the reliability and adaptability of engineering predictions.

3.4 Modeling damage-aeroelastic coupling

Damage-aerodynamic-elastic coupling modeling is the core challenge in the structural design of CMCs for hypersonic engines, as shown in Fig.12[100]. Its essence lies in dynamically correlating the cumulative damage evolution process of materials under multiple factors such as heat, force, and chemistry with the aerodynamic elastic response, in order to achieve precise prediction of structural lifespan and stability. This process requires breakthroughs in key technologies such as real-time tracking of damage evolution, design of multi-field coupling algorithms, and uncertainty quantification. Through cross-scale modeling and experimental verification, a closed-loop analysis framework of "damage initiation-expansion-failure" and "aerodynamic load-structural response" is constructed.

At the level of integrating damage models with aeroelastic analysis, CDM has become the mainstream tool. Tsunematsu et al.[101] studied composite panels with embedded delamination damage and showed that incorporating damage into the large-deflection plate equations significantly alters aeroelastic stability. They found that delamination-induced stiffness degradation remarkably decreases the first-order flutter critical speed, confirming that structural damage exerts a superlinear destabilizing effect.

Transient thermal shocks can induce an immediate reduction in stiffness, with Young's modulus dropping by about 7.5% after a single shock event, highlighting the rapid degradation caused by thermal loading[102]. Daub et al.[103] observed in coupled aero-thermo-structural experiments that incident shock waves at large angles can trigger flutter even in otherwise stable configurations, consistent with the "thermal-membrane buckling and shear instability" mechanism. Wang et al.[104] further demonstrated through thermal-modal analysis that elevated temperatures reduce the natural frequencies and stiffness of aerodynamic structures. Ye et al.[105] found via uncertainty analysis that variations in fluid temperature near the leading edge have the largest influence on flutter critical speed and frequency. Other studies using nonlinear thermal panel models and high-fidelity FSI have shown that thermal softening combined with boundary-layer or shock interactions can lower the flutter threshold and modify the limit-cycle oscillation characteristics. Cohesive-zone modeling approaches have been applied to capture crack initiation, growth, closure, and related hysteresis, providing a framework to link interfacial damage evolution with changes in flutter side-band width[106]. Materials-side experiments have consistently confirmed that high-temperature and thermal-shock conditions cause significant reductions in strength and modulus of CMCs[107].

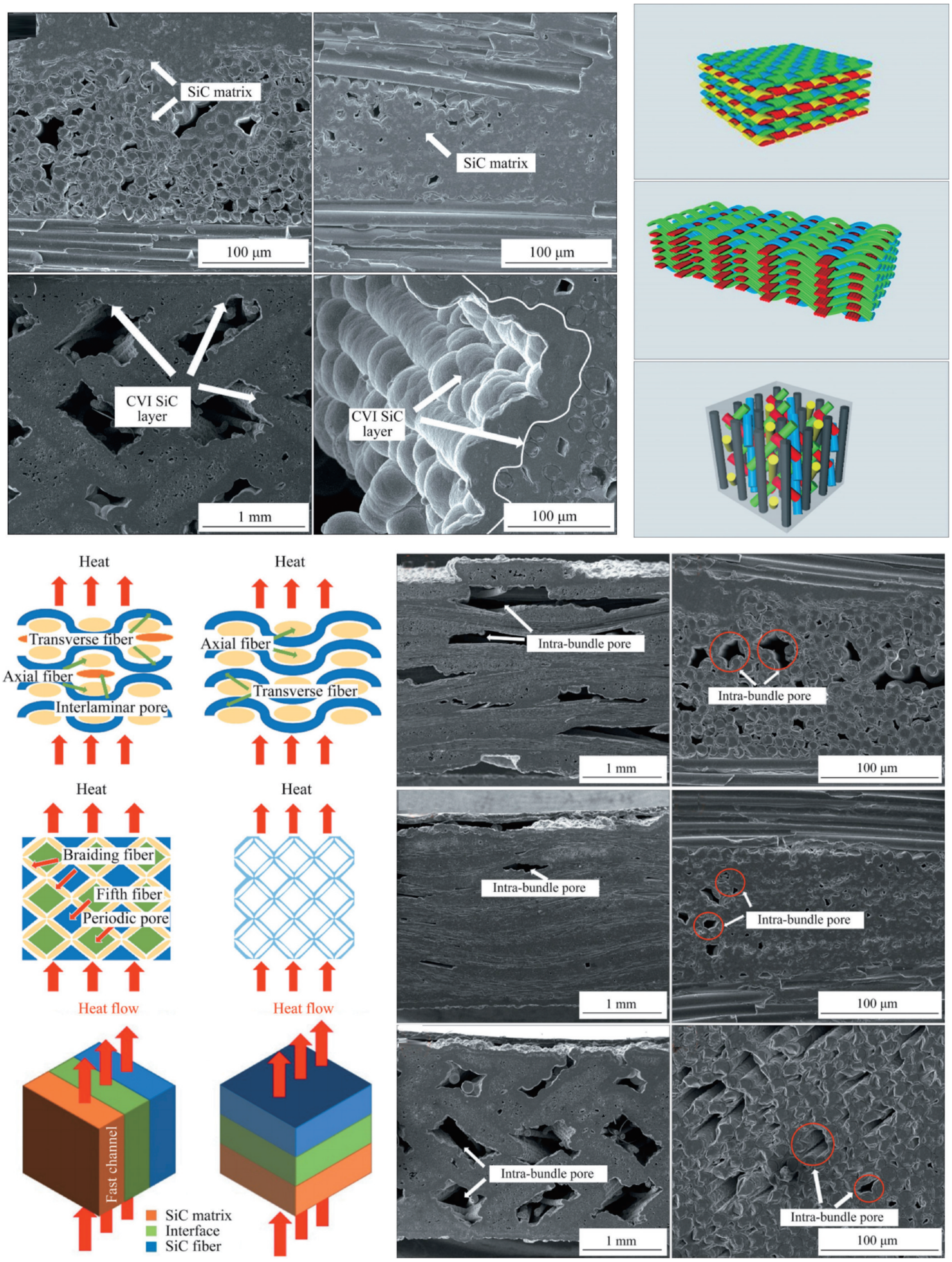

Fig.12 Damage-aeroelastic coupling model[100]

The data-driven method also demonstrates unique advantages, such as the real-time Bayesian calibration method proposed by Gao et al.[108], which combines experimental data to dynamically update parameters, increasing the efficiency of nonlinear response prediction for C_f/SiC composite materials by 3 times.

The multi-field coupling algorithm and the real-time update strategy are the key to achieving precise analysis. In the CFD/FEM partitioned coupling framework, the damage-driven local stiffness needs to be updated at each load step. The time-temperature-dependent damping model reveals that at 900 ℃, the proportion of interface friction energy consumption increases from 30% to 65%, and the damping increases by 4.3 times compared to that at ambient/room temperature[109]. Combined with stiffness degradation, a "frequency decrease and damping increase" dual effect is formed, which modifies the high-order mode flutter criterion. Uncertainty quantification is also indispensable. The Leyland team research[74] showed that a disturbance of $\pm 3°$ in the fiber placement angle can cause the flutter speed standard deviation to be as high as 12%. It is necessary to quantify the damage-modulus statistical uncertainty through the Bayesian framework or Latin hypercube sampling.

The core challenges in this field lie in the spatio-temporal nonlinearity of damage evolution and the multi-field synergy effect. In the aspect of thermal-damage coupling, the model proposed by Kuriakose et al.[110] showing that the critical dynamic pressure gap is 18% between 300 K and 600 K conditions, indicates that passive/active compensation strategies are needed to reduce thermal stress. Poursaeidi et al.[111] investigated GEF9 gas turbine blades and confirmed that cooling channel blockage caused a temperature rise of about 100 ℃, accompanied by an increase in TGO thickness to 5 μm and intensified TBC delamination. These effects ultimately triggered thermal overload failure, thereby verifying the significant influence of cooling efficiency on damage evolution. The balance of computational efficiency and accuracy is achieved through reduced-order models and local refinement techniques.

Experimental verification and engineering application provide crucial support for the theoretical model. In the damage-aerodynamic elasticity experiments under high-temperature conditions, Jia et al.[112] used high-temperature digital image correlation technology to achieve in-situ observation of the strain field on the surface of C_f/SiC at 1 300 ℃, discovering the thermal expansion non-uniformity caused by interface debonding above 1 000 ℃, providing direct visual evidence for damage evolution. In the analysis of key components of the engine, the research on turbine blade flutter suppression identified the high-frequency disturbance modes induced by damage through spectral orthogonal decomposition (SPOD), and the proposed active suppression strategy increased the flutter margin by 12%. The analysis of cooling channel blockage effect clarified the importance of thermal management in damage suppression, providing a basis for reserving cooling redundancy in blade design.

Future research needs to further break through the deep integration of intelligent materials and active control, high-performance computing-driven high-precision real-time simulation, and the full-chain quantification of multi-physics field uncertainties, to provide core theoretical support for the lightweight and long-life design of hypersonic equipment.

3.5 Multi-scale coupling modeling methods

The unique hierarchical microstructure of CMCs dictates that their macroscopic thermo-mechanical behavior is inherently linked to structural configuration occurring at the micro- and meso-scales[6,113]. Multi-scale modeling, therefore, becomes essential for accurately predicting the performance and durability of CMC components under extreme operating conditions. Examples of multi-scale coupling method researches were shown in Fig.13[114-115]. These models aim to bridge the gap between the constituent material properties, microstructural architecture, and the overall structural response[114-115], accounting for the complex interactions and failure mechanisms that arise at different length scales.

The stratified homogenization method, as an early mainstream strategy, achieves cross-scale information transmission through a bottom-up scale progression. Its core idea is to conduct mechanical analysis on representative volume elements at the lower scale, calculate the equivalent macroscopic material properties, and then use them as input for the FEM at the higher scale. Previous studies[116-117] have all adopted this method, converting random microscale features such as pore and fiber distributions into temperature-dependent equivalent moduli, which are used as "material cards" in the macroscopic FEM. This method has high computational

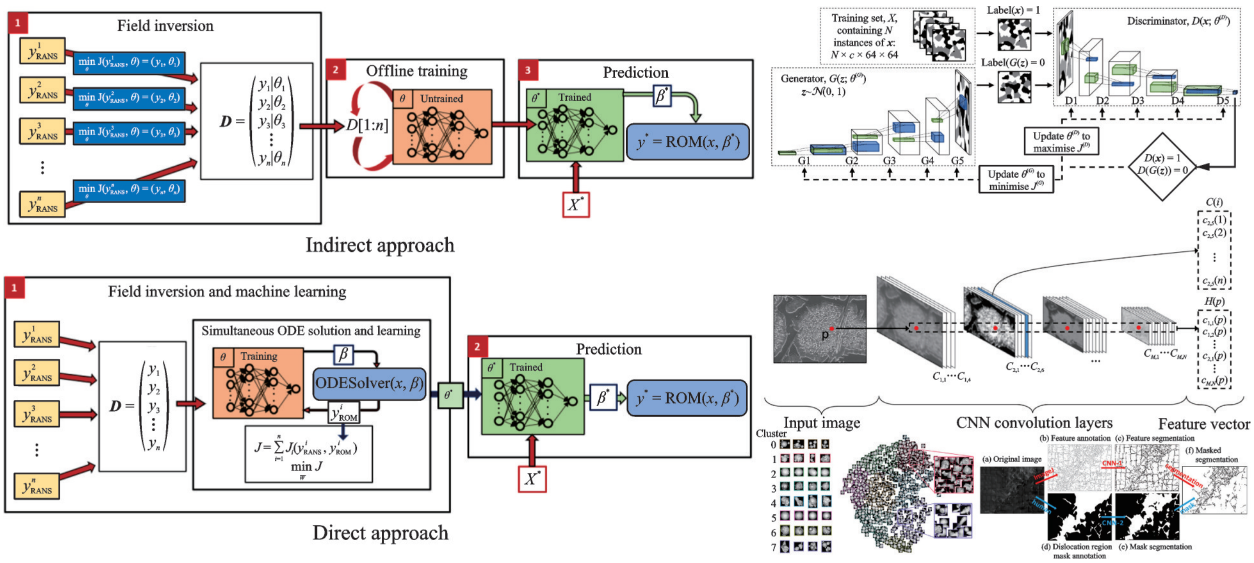

Fig.13 Examples of multi-scale coupling method researches[114-115]

efficiency and can be compatible with the existing macroscopic finite element framework, and is widely applied in the prediction of the mechanical properties of CMCs. However, the traditional homogenization method has the limitation of one-way information transmission, which may smooth out the macroscopic response mutations or inhomogeneities caused by microscale nonlinearity, and is difficult to capture the sudden drop in macroscopic stiffness caused by local damage concentration.

Recent studies have further demonstrated how weave architecture and interfacial design at the microscale directly govern macroscopic damage evolution. Mazars et al.[118] conducted in situ CT experiments on 3D-woven SiC CMCs and revealed that microcracks initiate via fiber-matrix interfacial debonding and propagate along tow boundaries, highlighting the role of weave architecture in directing crack paths. Carrère et al.[119] showed that the inclusion of tailored interphases increases interfacial shear strength and enables crack deflection and energy dissipation enhancement. Saleh et al.[120] reviewed the mechanical behavior of 3D-woven composites and noted that z-binder fibers effectively delay delamination, contributing to enhanced damage tolerance. Stegschuster et al.[121] demonstrated that architected weave patterns introduce tortuous crack paths and elevated mode-I fracture energy. Most strikingly, Tan et al.[122] combined phase-field and cohesive-zone modeling to show that 3D fiber bridging can increase dissipated fracture energy by over three orders of magnitude, underscoring the profound toughness advantage conferred by 3D weave architectures. Thus, these findings provide clear evidences that microscale crack initiation and mesoscale architecture strongly influence macro-scale stiffness degradation and toughness, reinforcing the need for multiscale coupling models that can explicitly capture architecture-driven damage mechanisms.

To overcome these limitations, the concurrent multi-scale method achieves more accurate cross-scale mapping through real-time bidirectional coupling. Compared to unidirectional homogenization, this approach can accurately capture the macroscopic stiffness drop caused by the nonlinear local cracks. Skinner et al.[123] mapped residual thermal stress, manufacturing defects, and temperature-dependent damage to the microscale model, and then pushed the real-time updated stiffness-damping matrix to the macroscopic level, solving the problem of "the need to refresh the unit properties in real time with temperature", and better conforming to the high-temperature service characteristics of CMCs. The finite element square (FE^2) method is a typical representative of this approach. By nesting the microscale RVE model at the macroscopic integration points and using the macroscopic strain as the boundary condition for the RVE, it solves the microscale response to obtain the stress and damage state at the macroscopic integration points, achieving dynamic feedback between scales. However, this method has extremely high computational cost-each integration point of the macroscopic structure needs to independently solve the microscale RVE, making it difficult to be applied in engineering in three-dimensional complex component analysis.

In recent years, the physical-data-driven hybrid multi-scale model has become the key to breaking through the efficiency bottleneck. Kim et al.[124] combined multi-scale finite element networks (DNN) and modeled at the microscale (fiber/matrix) and mesoscale (screw structure) separately, introducing stress amplification factors for cross-scale stress transfer, and the generated training dataset enabled the DNN to quickly predict the stress-strain curves for tension, compression, and shear, with good agreement with experiments. The method replaces part of the constitutive solution with the data-driven approaches, significantly improving computational efficiency, achieving online correction of the damage-induced stiffness degradation for the flutter threshold, as well as significantly reducing the wall time for concurrent computations. Furthermore, the application scope of the multi-scale method has been further expanded in special scenarios, enriching its application boundaries. Wang et al.[125] integrated the DMTO algorithm with Hashin, Hoffman, and Tsai-Wu failure criteria, and through the optimization verification of CFRP laminated structures, found that although the Tsai-Wu criterion reduced the failure index by 40%, it sacrificed the most flexibility, providing a basis for the selection of failure criteria in the multi-scale optimization of CMCs. Teng et al.[126] developed air-filled yarn fabrics through bionic structure design and CFD simulation. The multi-scale analysis of their thermal insulation mechanism also provided a new idea for the correlation between the microscale and macro-scale performance of CMC hot structures.

In conclusion, the multi-scale coupling modeling method achieves the precise mapping of "microscopic mechanism-detailed response-macroscopic behavior" of CMCs through strategies such as hierarchical homogenization, concurrent coupling, and physical-data fusion. However, its application still requires a trade-off between computational accuracy and efficiency. The hierarchical homogenization is suitable for engineering preliminary design, concurrent multi-scale is applicable for detailed analysis of key components, and the data-driven fusion model provides a new path to balance the two. Future development needs to further strengthen the physical constraints of cross-scale damage evolution and improve the parallel efficiency of the model to meet the engineering requirements of "high fidelity-high efficiency" in the aeroelastic analysis of CMCs.

3.6 Coupled flutter analysis methods

After establishing a numerical model considering the coupling effects of multiple physical fields, the ultimate goal is to determine the dynamic stability boundary of the CMC structure within the operating envelope through flutter analysis, which is crucial for ensuring the safety of key components such as turbine blades and combustion chamber walls. Currently, the coupling flutter analysis methods are mainly divided into frequency domain methods and time domain methods. The examples of coupling flutter analysis methods were shown in Fig.14[27,127-128]. Both have their own focuses in handling non-linearity, computational efficiency, and applicable scenarios. Meanwhile, the development of reduced-order model technology provides key support for balancing accuracy and efficiency.

The frequency-domain method, as a classic approach for analyzing linear or weakly nonlinear systems, converts the motion equations into the frequency domain through Fourier or Laplace transforms for solution. The core of this method is to linearize the coupling effect and embed it into the system matrix, and determine stability by using eigenvalues. Its advantages lie in high computational efficiency and suitability for quickly obtaining the flutter boundary. Abbas et al.[129] used the third-order piston theory combined with geometric nonlinearity to analyze the thermal- and aerodynamic-structural problem, demonstrating the influence of temperature loads on the flutter behavior. Zafer et al.[130] proposed a static and flutter analysis method for thermal- mechanical coupling, using the classical plate theory and piston theory, applicable to any temperature gradient, and is a new method for multi-physics

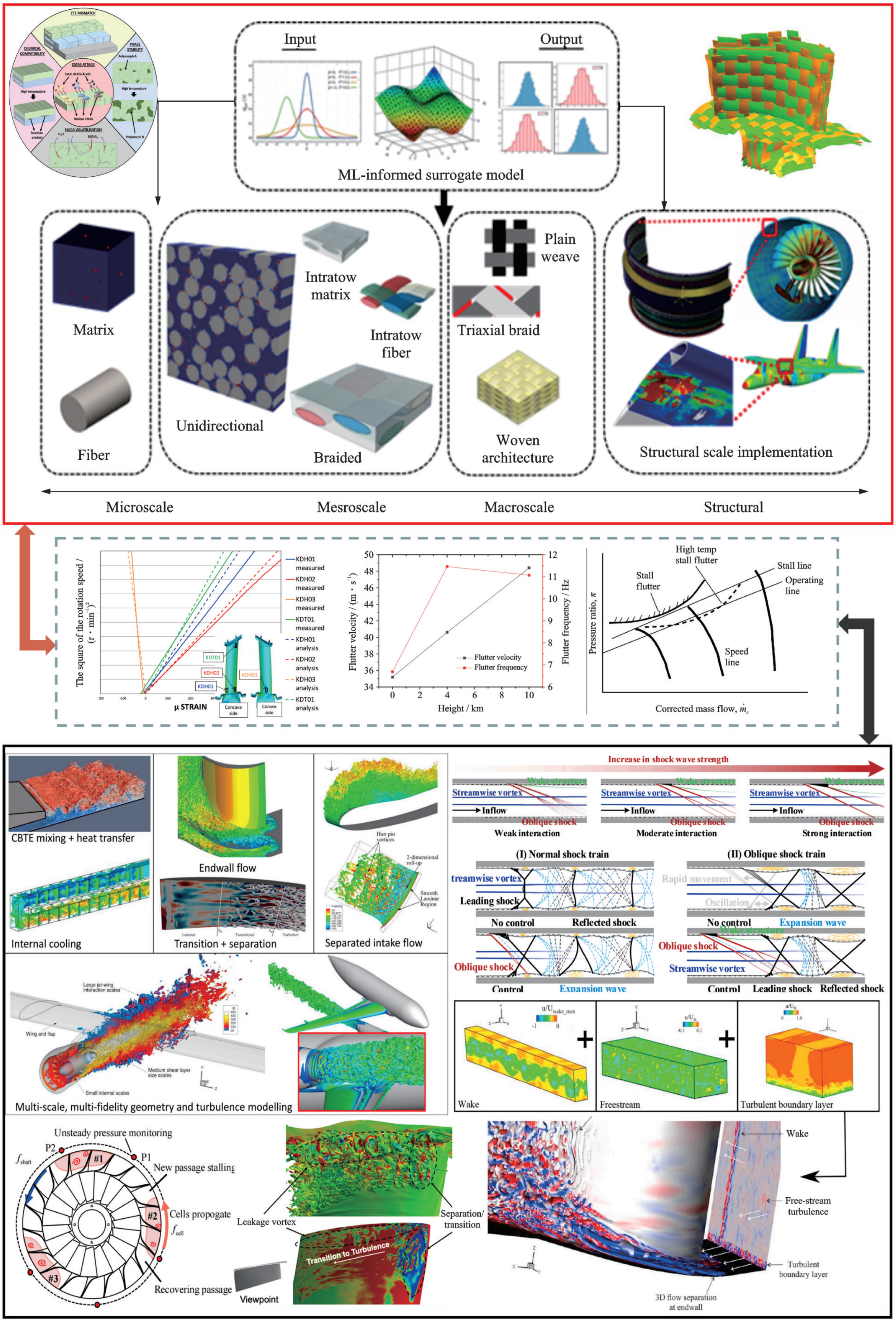

Fig.14 Examples of coupled flutter analysis researches[27,127-128]

coupled frequency-domain analysis. Cao et al.[131] conducted characteristic analysis on laminated plates in hypersonic yaw flow, revealing that the "transverse shear mode-thermal softening" synergy led to a reduction of the threshold dynamic pressure by approximately 18%. However, the frequency-domain method is difficult to directly handle strong nonlinear coupling and time-varying characteristics, limiting its application in extreme environments for the evolution scenarios of CMCs with severe damage.

The domain method directly integrates the coupled nonlinear aerodynamic-thermal-structural control equations to simulate the evolution of the response over time, thereby determining the stability of the system. It is naturally well-suited for strong nonlinearity and system time-varying characteristics, and has higher accuracy: Li et al.[132] conducted a large deflection time-domain analysis of the bent-twist-coupled wind turbine blade, confirming that nonlinear modal coupling is the root cause of the "multi-order mixed" vibration of large-scale composite blades. However, the time-domain method requires long-term dynamic simulation and small-time steps to capture high-frequency responses, resulting in extremely high computational costs, and faces challenges in large-scale parameterized research in engineering.

To break through the bottleneck of computational efficiency, the reduced-order model technique has become crucial. By constructing a simplified low-dimensional model based on a high-fidelity model, the computational load can be significantly reduced while retaining the main dynamic characteristics. For instance, Albarakati et al.[133] developed the "Sliding Window POD (SW-POD)", which dynamically adjusts the modes to cope with unsteady systems and significantly improves the RMSE and the number of samples in the L96 model's multi-excitation state switching. Dai et al.[134] proposed the enhanced subspace adaptive POD, which combines stage SVD and error threshold-triggered updates, reducing the number of modes and computational overhead while maintaining the stability of the approximate error. These techniques provide efficient tools for parameterized research and the development of online control models.

Furthermore, the control and mechanism analysis of flutter in special scenarios have enriched the methodological framework. Kouritem et al.[135] controlled the quality-stiffness distribution by selectively attaching copper sheets to the composite material panel, which increased the flutter critical pressure by 120.9%, thereby verifying the enhancement effect of structural optimization on stability. D'Aniello et al.[136] were the first to apply Doak momentum potential theory (MPT) to the unsteady self-excited oscillation of the PRECCINSTA burner. They combined LES with modal decomposition to separate acoustic, vortex, and entropy disturbances, revealing that the near-phase coupling of acoustic entropy disturbances in the injection area is the main driving mechanism of the self-excited feedback loop, providing a new perspective for the study of engine combustion chamber flutter mechanisms. Scholten et al.[137] proposed a non-coupled static aeroelastic analysis method. By presetting parameters to fit and constructing fluid and structure surrogate models, it solved the velocity problem faster than traditional coupled methods by more than a hundred times, making it suitable for rapid evaluation in the preliminary design stage.

In conclusion, for coupled flutter analysis, a balance between accuracy and efficiency needs to be achieved in the method selection: The frequency domain method is suitable for rapid analysis of linear/weakly nonlinear systems, the time domain method is suitable for detailed studies of strongly nonlinear systems, and the reduced-order model is the core technology that balances the two. The current key challenge in this field lies in the contradiction between complex multi-physics coupling, highly nonlinear behavior, and computational cost. In the future, it is necessary to further develop high-precision time-domain algorithms applicable to the damage evolution of CMCs, dynamic adaptive reduced-order models, and flutter prediction models for online monitoring and real-time control, to promote the transformation of theoretical methods into engineering applications.

4 Research Status, Challenges and Future Concerns

The coupling of aerodynamic, thermal and structural mechanics in engine CMC structures involve extreme environment multi-physics field coupling, complex material high-temperature behavior evolution and structural dynamic response sensitivity. It is a highly challenging frontier research hotspot in the aerospace field. Based on the modeling and analysis methods described previously, researchers have made certain progress in understanding the mechanism of complex phenomena, developing predictive tools and evaluating the behavior of CMC structures in engine environments. However, there are still severe challenges at the theoretical, computational and experimental levels. This chapter aims to summarize the current overview of engine CMC structure coupling aerodynamic elasticity research, analyze the core challenges, and outline future key research concerns to provide references for the development of this field.

4.1 Current research status and advances

The deepening of aerodynamic-thermal-structural coupling analysis is the most fundamental and extensive field in engine aerodynamic elasticity research. A large number of research works through numerical simulation and theoretical analysis have generally confirmed that the aerodynamic heating effect has a significant impact on the flutter boundaries of engine structures (especially CMCs, which are materials sensitive to temperature)[1,5]. High temperatures usually lead to a decrease in the elastic modulus of CMC materials, the generation of thermal stress, and ultimately a decrease in the overall stiffness of the structure, resulting in a reduction in the flutter critical speed and changes in the flutter frequency[15,22]. Researchers[36,48] have been able to conduct transient thermal-aerodynamic elasticity analyses of some typical structures to reveal the dynamic interaction process between the dynamic evolution of the temperature field and the structural dynamic response. In recent years, some studies have begun to pay more attention to the real gas effects in engine flow and the precise prediction of the aerodynamic thermal environment and aerodynamic forces caused by possible chemical reaction flows[51,58,63], and attempt to incorporate these more detailed physical models into the coupled aerodynamic elasticity analysis. Incorporating the influence of temperature on material properties and the thermal stress effect caused by temperature gradients into the finite element model of the structure has become a standard practice for conducting engine structure aerodynamic elasticity analysis. Studies[35,55,79] have also shown that not only the change in material elastic modulus with temperature has a direct impact on the structural stiffness, but also the thermal stress caused by non-uniform temperature distribution or anisotropic thermal expansion can significantly affect the geometric stiffness of the structure, and this pre-stress effect can have a significant impact on the natural frequency and mode of vibration of the structure, as well as ultimately on the flutter characteristics. This effect is particularly prominent for thin-walled structures or slender components with relatively simple geometries.

CMCs are quasi-brittle material, thus internal damage initiation and accumulation inevitably occur when they are exposed to the extreme environment of the engine, and this damage evolution is crucial to the long-term stability and flight safety of the structure[61,84]. Therefore, researchers have begun to attempt to embed material models describing CMC damage behavior into the framework of aerodynamic elasticity analysis in order to evaluate the dynamic impact of damage accumulation on the flutter boundaries of the structure[138]. Preliminary numerical simulation results[139] have shown that the structural stiffness degradation caused by material damage induced by cyclic loading or continuous high-temperature environment does indeed causes a further reduction in the flutter critical speed, and in some cases[79,86], it may also change the mode of flutter occurrence. However, it should be noted that this research is still at a relatively preliminary exploration stage, and the adopted damage models still have considerable room for improvement in terms of accuracy, application scope and coupling efficiency with the dynamic aerodynamic elasticity analysis process.

In order to more accurately obtain the complex microstructure features within CMCs materials and their intrinsic influence on macroscopic mechanical behavior and aerodynamic elastic responses, multi-scale modeling methods have been initially applied to obtain equivalent macroscopic performance parameters of CMC laminates or woven composite materials, and these parameters are used in subsequent macroscopic structural aerodynamic elastic analyses[10,86]. To a certain extent, this method improves the accuracy of describing the anisotropy and non-uniformity of the materials. However, directly applying the computationally more demanding concurrent multi-scale methods to the full-scale engine CMC structure coupling aerodynamic elastic simulation, which involves complex geometries and long dynamic processes, still faces significant obstacles in terms of computational resources and efficiency. As repeatedly emphasized earlier, numerical simulations based on high-fidelity multi-physics coupling models usually come with huge computational costs, which greatly limits their application in parametric studies, optimization design, and control law design in the early stages of engineering design. Therefore, developing reduced-order model techniques that can significantly reduce computational costs has become a very important research direction in this field.

Currently, based on classical model reduction methods such as modal analysis, eigenorthogonal decomposition, and balance truncation, these methods have been applied in some relatively simplified the coupling problems of aerodynamic-thermal-structural and have shown good computational efficiency and acceptable prediction accuracy within specific parameter ranges[93,98]. However, how to construct stable, reliable, and efficient reduced-order models for complex systems with strong nonlinearity, strong multi-physics coupling, and significant time-varying characteristics remains a challenging research topic.

Due to the extreme nature and complex multi-field coupling of the engine environment[73,80], it is extremely difficult to fully and precisely replicate this comprehensive environment in ground experimental facilities. As a result, related experimental research is very limited and challenging. For example, some experimental work attempts to combine external heating devices in subsonic or supersonic wind tunnels to study the influence of thermal effects on the aerodynamic elastic stability of typical structures. Additionally, facilities such as arc heaters and plasma wind tunnels are used to produce high-temperature, high-speed airflow to study the thermal response and ablation behaviour of materials. However, to achieve a fully coupled aerodynamic elastic experimental verification platform that can precisely simulate all key factors such as high Mach number flow, high dynamic load, extreme temperature and heat flow distribution, complex flow field structure, and the dynamic evolution of material internal damage, it is currently still a huge technical obstacle, which greatly limits the full validation and calibration of complex numerical models. Nevertheless, important progress has been made in recent years. For example, the high-temperature fatigue and thermo-mechanical fatigue (TMF) experiments have been carried out to capture stiffness and life degradation of woven SiC/SiC composites with EBC coatings, revealing strong temperature-phase effects and oxidation-assisted fatigue mechanisms[140]. In addition, in-situ optical full-field techniques such as digital image correlation (DIC) have been extended up to 1 600 ℃ to measure displacement and strain evolution, and these experiments demonstrated that at around 1 300 ℃ C/SiC composites undergo a brittle-to-ductile transition accompanied by significant microcrack evolution. For non-contact flutter detection, laser Doppler vibrometry (LDV) and scanning LDV methods have been widely adopted to measure high-resolution vibration modes in aeroelastic structures. These techniques allow precise tracking of modal drift under combined aerodynamic and thermal loads, thereby providing critical validation data for flutter prediction models. More comprehensive aerothermal-structural wind tunnel facilities have also been utilized, where DIC and PIV were combined to synchronously capture structural response and shock-boundary layer interactions during flutter onset. Aerothermoelastic experiments in hypersonic wind tunnels, such as the DLR H2K facility at Mach number of 5—8, provided benchmark datasets on coupled flow-thermal-structure responses, while NASA's arc-jet IHF facilities enabled testing of thermal protection and composite structures under combined convective and radiative heating with fluxes up to several megawatts per square meter[85-86].

These experimental work, although still limited compared to the diversity of numerical models, has significantly enhanced validation capability. Importantly, comparisons show that CFD simulations often overpredict flutter margins when transitional shock-boundary layer interactions are not resolved, while oxidation and thermal stress effects are sometimes underestimated in fatigue life models, leading to discrepancies up to an order of magnitude. Nevertheless, the combination of high-fidelity measurement technologies such as high-temperature DIC and LDV with advanced wind tunnel facilities has provided an increasingly reliable basis for calibrating and validating numerical models, forming an indispensable link between computational prediction and engineering application.

4.2 Main challenges

Although the research on the coupling aerodynamic elasticity of engine CMC structures has made certain progress, it still faces a series of key challenges: The extremely high computational cost and efficiency bottleneck are currently the most prominent problems restricting the development of this field. Performing multi-physics coupling numerical simulations involving high-fidelity CFD simulations, refined material damage models, or concurrent multi-scale analysis often requires the use of large-scale parallel computing clusters and takes days, weeks, or even longer computational time. Such high computational costs make it difficult to apply high-fidelity models widely in the early stages of engineering design, where rapid iteration and extensive parameter studies are required, and they also limit the in-depth investigation of more complex phenomena[1,3,131].

The uncertainties in model accuracy and physical fidelity are manifested as follows: The completeness and accuracy of material constitutive and damage models remain a long-standing unresolved problem, especially under extreme temperatures, complex stress states, and special chemical environments. Accurately characterizing the highly nonlinear, significant anisotropy, creep and stress relaxation, as well as damage initiation, propagation, saturation, and ultimate failure processes of CMC materials throughout their constitutive relationships and damage evolution laws. Particularly, the lack of sufficient, reliable, and parameterized experimental data obtained under these extreme and coupled conditions has brought significant difficulties to the establishment of the model, parameter calibration, and validation of its effectiveness. The accuracy and applicability range of aerodynamic/thermal models are challenged by the extreme complexity of hypersonic flows themselves. To precisely simulate these complex physical phenomena, extremely high requirements are imposed on numerical formats, grid quality, turbulence models, real gas models, and chemical reaction kinetics models of CFD methods[58,61]. Coupling these with structural dynamics, heat conduction, and material damage evolution processes undoubtedly increases the complexity of modeling and computational uncertainty. The robustness, stability, and efficiency of coupling algorithms face challenges. Partition algorithms may encounter difficulties in ensuring the convergence and stability of numerical calculations, especially when the time step selection is inappropriate or the characteristics of the physical field vary significantly. Theoretically superior overall methods are difficult to be promoted due to their extreme complexity in implementation and huge demand for computing resources[26]. Therefore, how to further improve the computational efficiency, numerical stability, and universality of coupling algorithms while ensuring the accuracy of coupled calculations is a key technical bottleneck in the research of coupling analysis methods. The extreme difficulty in experimental verification and model calibration has made it extremely difficult to conduct sufficient and effective experimental verification and parameter calibration of the developed complex multi-physics coupled numerical models.

The lack of reliable experimental data as a "benchmark" makes it difficult to fully ensure the confidence in numerical simulation results and limits the strict evaluation of the rationality of various simplifications and assumptions in the model. The complexity of uncertainty quantification and reliability assessment stems from the presence of various uncertainty sources in the coupled aerodynamic elastic analysis of engine CMC structures[31,55,82]. These uncertainty factors ultimately transfer and accumulate to the prediction results of critical performance indicators such as flutter boundaries, making them also have certain uncertainty. How to effectively perform uncertainty quantification in such a complex multi-physics coupled analysis framework and conduct scientific assessment of the flutter reliability of CMC structures based on this is an urgent challenge with significant engineering significance. The "gap" in the correlation of multi-scale physical mechanisms is manifested in how to efficiently and accurately connect the material behaviors that occur at lower scales, which are usually highly localized and nonlinear, with the complex coupling mechanism between these behaviors and the overall dynamic response of the structure at the macroscopic scale. Especially in dynamic, strongly coupled, and multi-physics acting environments, there still exists a huge theoretical and computational "gap" that needs to be crossed.

4.3 Prospects for future research concerns

To effectively address these numerous challenges and promote the continuous progress in the field of engine CMC structural coupling aeromechanical elasticity research, future research efforts should focus on the following strategic and forward-looking directions: Developing efficient, high-precision, and highly robust multi-physics field coupling algorithms and solvers, continuing to optimize and improve existing partitioned coupling strategies, such as developing more advanced prediction-correction iterative formats, adaptive sub-cycle techniques, and interface relaxation techniques for specific coupling problems, to enhance their stability and convergence speed. Skinner et al.[123] established a multi-scale thermal-structural-chemical damage model, which has achieved precise capture of residual stress and nonlinear behavior of CMCs during high-temperature manufacturing, providing an important reference for the analysis of complex coupling mechanisms. At the same time, it is necessary to explore new overall solution methods applicable to ultra-large-scale parallel computing environments, such as parallel implicit algorithms based on domain decomposition and multigrid methods, in order to achieve higher accuracy in solving strongly coupled problems at acceptable computational costs. Vigorously research and apply adaptive grid technology and time step control strategies to intelligently allocate computing resources to critical regions and time periods with significant physical field variations. Kamkar et al.[141] developed a heuristic AMR method based on feature monitoring and error estimation, achieving efficiency breakthroughs in vortex-dominated flows. The technical ideas of these methods can provide support for the efficient simulation of complex flow fields in engines. Breakthroughs in reduced-order modeling techniques for strongly nonlinear multi-physics systems, surpassing traditional linear reduced-order models (ROMs) methods, and the development of nonlinear ROMs capable of handling geometric, material, contact nonlinearity, and strong coupling of multiple physical fields are needed. Fonzi et al.[142] proposed a physical-data-driven hybrid ROM architecture, which has been verified for its scalability and nonlinear capture capability in nonlinear coupling systems. Parametric dynamic mode decomposition (DMD) offers a promising route for constructing adaptive parameterized ROMs in highly flexible structures. A linear parameter-driven ROM based on this method has already demonstrated its practicality, providing a concrete example of how adaptive ROMs can be designed to accommodate parameter variations[143]. Additionally, it is necessary to explore new paradigms combining data-driven and physics-based approaches to further expand the applicability of such methods.

Capturing nonlinear failure behaviors of woven CMCs under extreme loading requires multiscale modeling approaches that account for microstructural complexity and fiber spatial randomness. Advances in this direction have shown that explicitly considering these features significantly enhances predictive fidelity for nonlinear responses, as demonstrated by a modeling framework developed for two-dimensional woven CMCs[144]. Huang et al.[145] proposed a macro-micro combined finite element model-based inverse identification method, which integrates μCT-reconstructed microstructures, a BP neural network, and a trust-region algorithm to achieve highly accurate and robust inversion of the elastic parameters of CMCs. Their work demonstrated the regulatory mechanism of microstructural features on macroscopic stiffness behavior. Santhosh et al.[146] employed a micromechanical model to analyze the stress-life behavior of two-dimensional woven CMCs, linking inherent microscale damage mechanisms to the overall structural performance and lifetime predictions, further highlighting the significance of micro-macro interactions. Enhance the high-fidelity modeling and coupling capabilities of complex aerodynamic physical processes in engines, and improve CFD/CHT methods to accurately simulate turbulent transition, shock-boundary layer interference, real gas effects at high temperatures, and plasma effects. At the same time, the focus is on researching efficient coupling algorithms for gas physical processes and structural dynamics, material thermal response, and surface damage, especially for complex interface problems such as moving boundaries and multiphase flows[147-149]. Breakthrough ground experimental testing technologies and diagnostic methods are developed, and new facilities capable of simulating extreme coupled environments are constructed. Corresponding online measurement technologies with non-contact and high spatiotemporal resolution are also developed to obtain key data such as flow fields, temperature fields, stress-strain, and damage states in real time. Additionally, efforts should be strengthened in the construction of flight test platforms, using real flight data to guide the direction of ground experiments and verify numerical models. Systematic coupling aerodynamic elasticity reliability analysis and robust design with multiple sources of uncertainty are carried out, uncertainty quantification (UQ) methods suitable for high-cost and highly nonlinear models are developed, a database of CMC material performance uncertainties is established, and the influence of manufacturing defects and environmental fluctuations on structural reliability is studied. Combining UQ with optimization design, robust design for reliability is carried out to reduce the sensitivity of structures to uncertain factors. Through continuous research in these directions, it is expected to overcome current bottlenecks, deepen the understanding of complex physical phenomena, improve the accuracy and efficiency of prediction models, and provide theoretical and technical support for the development of next-generation engines and safe flight.

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陶瓷基复合材料在先进发动机中的振动稳定性与颤振分析研究进展

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摘要:先进推进系统在极端服役条件下同时承受强烈的气动载荷和热载荷,其中颤振稳定性问题已成为制约陶瓷基复合材料(Ceramic matrix composites, CMCs)热端结构设计与安全运行的关键瓶颈。相比传统镍基高温合金,陶瓷基复合材料具备更优异的耐高温性能和比强度,是新一代发动机热端结构的理想选择。然而,陶瓷基复合材料的各向异性、非均质性及复杂非线性行为,与极端环境下的气动-热-结构、热-力及损伤-气动弹性等多物理场耦合作用相互叠加,显著增加了振动稳定性与颤振分析的复杂性。本文系统综述了近年来该领域的研究进展,重点包括多场耦合机理、材料本构与损伤演化模型、多尺度建模方法、耦合求解策略以及关键参数对颤振特性的影响;同时,指出了高温非线性建模复杂、耦合计算效率不足及复杂编织结构多尺度建模困难等挑战,并展望了未来的发展方向,为先进陶瓷基复合材料热端结构的设计与安全评估提供理论参考。

关键词:陶瓷基复合材料;振动稳定性;颤振;多场耦合;先进发动机