6.10
Design Approaches For High Temperature Composite Aeroengine Components

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6.10.1 INTRODUCTION

Actual and potential composite applications in commercial and military aircraft gas turbine engines range from low temperature graphite/polymer matrix composite (PMC) components at the front of the engine, such as fan blades, vanes, struts, and cases, to high temperature ceramic matrix composite (CMC) turbine, combustor, augmentor, and nozzle components. This chapter will address the design approaches for CMCs, although in many instances similar approaches also apply to PMCs.

Most CMCs in their "virgin" states exhibit higher specific mechanical properties than metals at temperatures exceeding 1600 °F, but CMCs are susceptible to long-term property degradation. Property degradation results from mechanical (static, low cycle fatigue (LCF), high cycle fatigue (HCF), impact, and thermal (steady state, transient) loads combined with chemical and environmental (moisture, salt fog, temperature, air, pressure, flow) exposure. Quantifying the synergistic effects of these on the long-term properties of composites is the key to designing lightweight durable composite components. Without this knowledge the designer must resort to ultraconservatism in the design process to ensure that the structural load carrying capabilities of the component are adequate for the intended life of the component. Although safety-of-flight is the primary concern in the design of structural composites for aeroengine applications, the financial liabilities resulting from premature component failure can be severe and must be accounted for in the design process.

Typical fighter aircraft and large transport aircraft engines are illustrated in Figures 1 and 2, respectively. Figure 1 illustrates an engine that is typical of those used in F–15 and F–16 fighter aircraft. Figure 2 illustrates an engine that is typical of those used in large commercial aircraft, such as the commercial Boeing 777 and Airbus A330 aircraft. As illustrated, the commercial aircraft engine has an inlet diameter almost twice that of the military aircraft engine. Inlet diameters on large commercial aircraft gas turbine engines can exceed 275 cm. Another major difference between the fighter and commercial aircraft gas turbine engines is the bypass ratio. The bypass ratio is the ratio of inlet air mass flow bypassing the high compressor and passing through the fan duct divided by the air mass flow passing through the high compressor. The commercial aircraft engine has a high bypass ratio, i.e., a large percentage of the fan air bypasses the high compressor

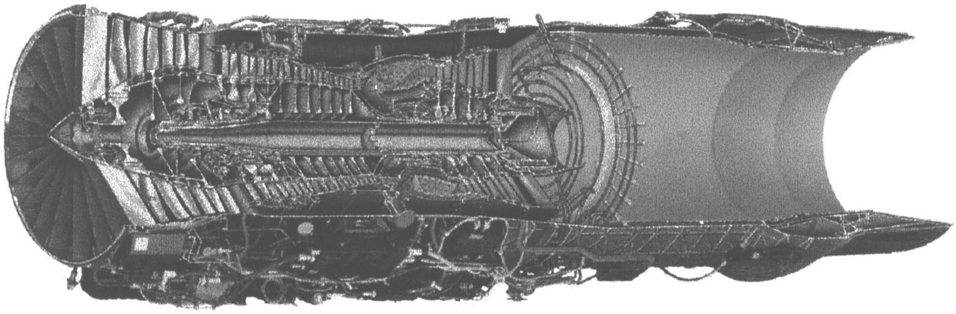

Figure 1 PW 229 military gas turbine engine.

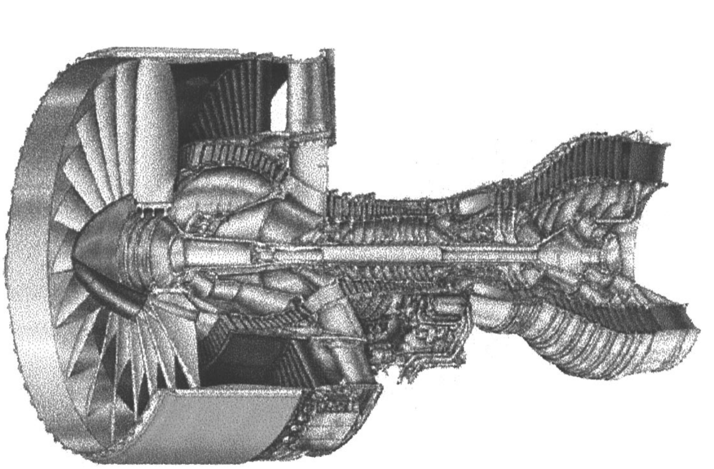

Figure 2 PW 4000 commercial gas turbine engine.

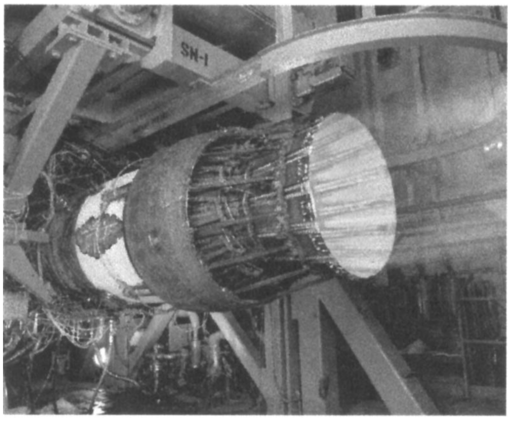

Figure 3 PW 229 test under augmented power.

providing a significant amount of the engine thrust. The fighter aircraft engine has a low bypass ratio and obtains its primary thrust from the air that exits through the nozzle. The bypass ratio for large commercial aircraft gas turbine engines is typically greater than five, whereas for fighter aircraft, gas turbine engines it is typically less than one. The fighter aircraft engine contains an augmentor (afterburner) which can provide additional thrust when fuel is ignited in the augmentor. Nozzle components are subjected to extreme temperatures during augmentor operation. Figure 3 illustrates an engine operating under augmentation on an engine test stand. Typically the augmentor is only used for short periods of time when additional thrust is required such as carrier launch, steep climbs, or combat maneuvers.

Figure 4 illustrates an axisymmetric and a rectangular nozzle on engines operating under augmentation in a test cell. The rectangular nozzle is operating in a vectored thrust mode. The capability to vector thrust improves aircraft maneuverability. The extreme temperatures of the hot gases require cooling air to maintain component temperatures within the design allowables of metals. Diverting air for cooling results in a loss of engine performance since less air is available for combustion. Therefore, materials which can operate at higher temperatures and maintain the required strength, stiffness, and thermal properties can provide increased performance.

Although there are currently no supersonic commercial transports in production, the advantages of reduced travel time remains evident. The current Concorde supersonic civil transport does not meet the environmental standards established for future production of commercial transports. CMCs may be an enabling material for combustor and nozzle components of any future supersonic civil transport propulsion systems. The environmental requirement to reduce nitrous oxides from the combustion process to levels which will not damage the ozone layer require advanced combustor designs. The high component temperatures may require the application of CMCs to achieve the design goals. The requirements to reduce the noise levels of supersonic aircraft to the strict standards imposed on subsonic aircraft increase the requirements for sound attenuation within the nozzle. The low density and high temperature capability CMCs may be required to achieve this goal. Future efforts to develop a supersonic aircraft will likely hinge on development of CMCs for the propulsion system.

Turbine, combustor, and exhaust nozzle components on military or future Supersonic Civil Transport commercial engines require cooling to maintain the maximum component operating temperatures within the capabilities of metal structures. The requirement for cooling air reduces the engine performance. Only ceramic, CMCs, or carbon matrix composites offer potential for operation at the extreme temperatures these components would experience without cooling air. However, designers have had difficulties in the past utilizing ceramics in structural components due to their low toughness and susceptibility to brittle fracture. Therefore, CMCs have been developed to provide the required toughness capabilities not achieved in monolithic ceramics. They are being actively pursued for application in gas turbine engines for combustor, turbine, and nozzle components.

CMC nozzle components offer significantly less development risk than combustor or turbine components as defined by three areas: (i) flight criticality, (ii) visual inspection, and (iii) repair or replacement. Therefore, nozzle components have provided the bulk of engine durability data since the 1980s, and will continue to do so as better CMCs are developed. Design of nozzle components will be emphasized in the following discussions.

6.10.2 DESIGN CONSIDERATIONS

6.10.2.1 CMC Design Guidelines

Cost and long-term durability are the key design drivers for CMCs for manned aircraft and land-based turbines. While material suppliers and fabricators must work to reduce the relatively high cost of CMC materials the designers must work with fabricators to develop designs which minimize fabrication costs. All CMC materials exhibit property degradation due to environmental exposure such as

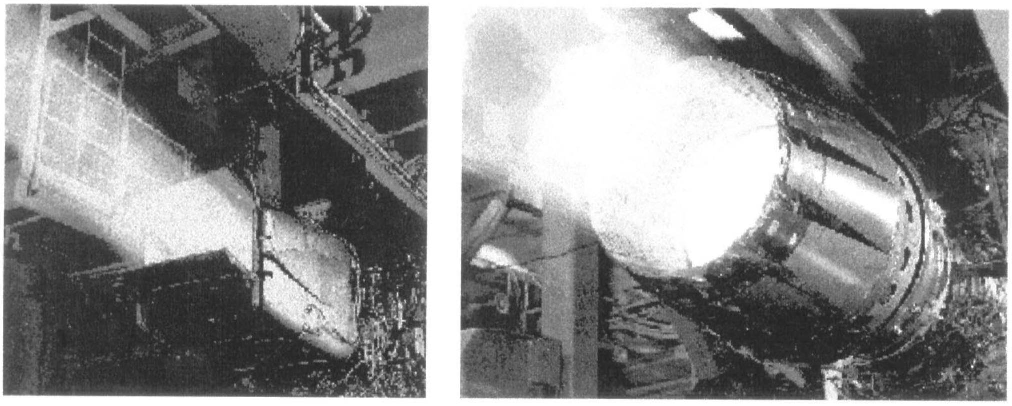

Figure 4 Axisymmetric and rectangular nozzle rig tests.

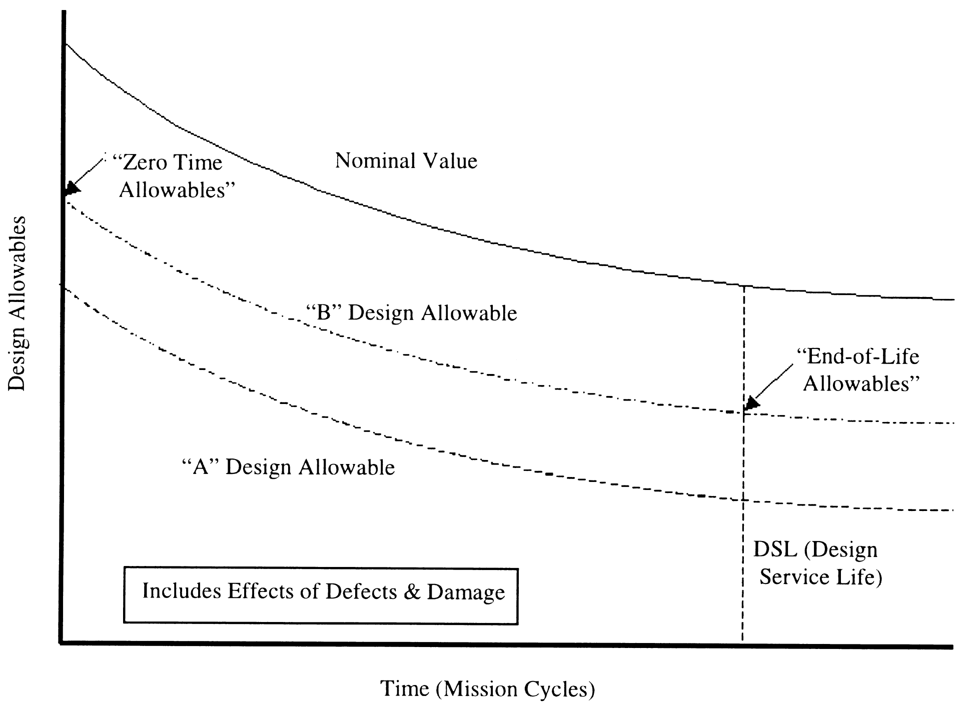

Figure 5 End-of-life design allowables

temperature, moisture, salt, fog, etc. Therefore, it is imperative that components are designed to the "end-of-life" allowables, as illustrated in Figure 5, which reflect the material strength after it has been subjected to the full mission environmental and load requirements, including, stress–strain, cycles, temperature, moisture, salt, fog, fluids, gas pressure, gas flow, and time. These effects must be evaluated in a synergistic manner as degradation is more rapid when the loads and environment are combined in the material characterization tests to represent actual mission conditions. These test data are incomplete on all CMC material systems requiring extrapolation to predict "end-of-life" allowables. Since full life testing is incomplete, the analytical procedures used to predict these allowables have not been validated.

CMCs exhibit microcracking under tensile stress, generally below 100 MPa, which results in accelerated degradation in the synergistic environment defined above. Components for long-term durability are typically designed for stress–strain levels below microcracking, but inadvertent overstress due to impact or handling could result in local damage. Therefore, long-term durability testing must include tests with precracked samples to evaluate any accelerated degradation due to local damage. Also, long-term durability tests should include open-hole coupons to evaluate the effects of stress concentration factors around open holes.

Testing has shown that stress concentration effects are more detrimental in long-term loading than in static fracture tests when compared to unnotched coupons. The localized damage near the surface of the hole which reduces the stress concentration effects in static-fracture tests is a region of accelerated property degradation in long-term durability tests. Therefore, for components that have cooling holes or attachment holes it is imperative that long-term durability tests include these effects.

Complexity is added to the test requirements since most CMCs exhibit an intermediate temperature strength degradation between 1000 and 1200 °F which can be as severe as high temperature degradation which occurs above 1800 °F. Therefore, these intermediate temperatures must be included when evaluating the long-term durability of CMC materials.

Near-term applications of CMCs are non-flight critical components and visually observable components, such as nozzle liners and seals. The lack of long-term durability data or validated life prediction methods limits the initial production application of CMCs primarily to nozzle components. These components should provide the required durability data to assess the long-term performance of these materials and to gain design confidence for additional applications.

6.10.2.2 Status of CMC Design System

The various components of the CMC Design System are statused as green (state-of-the-art), yellow (partially developed), or red (nonexistent).

The tools to perform the stress analysis of orthotropic materials such as CMCs exist both in closed form and finite element analysis (FEA) codes. A number of commercially available FEA codes contain orthotropic 3-D elements which provide the capability to determine the full 3-D stress state resulting in three normal and three shear stresses. These codes are capable of coupling the heat transfer analysis with the thermostructural analysis. Closed form laminate codes and 3-D architecture codes are also commercially available. Therefore, the status of stress analysis codes is green.

Life prediction of CMC materials has been the subject of significant research and development effort since the 1980s. Although these efforts have led to increased understanding of degradation mechanisms in CMC materials, there are currently no fully validated analytical life prediction tools available for any CMC materials. Since each class of CMC materials exhibit different degradation mechanisms, a universally applicable analytical life-prediction tool is not a realistic near-term goal. The current status of the purely analytical life prediction tool for any CMC is red. The empirical life prediction approach is classified as green since the type of tests and test methods to determine the life of CMCs is well understood as will be defined later in this chapter. The semi-empirical approach is classified as yellow. It relies heavily on curve fitting experimental data and extrapolating it outside of the test range.

The strength, elastic moduli, and physical properties of virgin CMC materials are generally available, although statistically reliable data are scarce. Funding to obtain statistically reliable properties for virgin material is not justified since components must be designed to "end-of-life" properties. Therefore, the status of virgin material properties is classified as green. These same properties for degraded materials are available in limited quantities. Additional long-term testing with synergistic effects is required. The environmental degradation effects on moduli and physical property data are generally not as critical as strength degradation and, therefore, are classified as yellow, although for components where the through-thickness thermal gradient drives the design, additional data on degraded through-thickness conductivity are required.

"End-of-life" strength data are severely lacking and the ability to predict the life of a structure past the time for which test data extends is unproven. Currently components can reliably be designed to a limited life as defined by the existing test data. Extending the life beyond this point requires extrapolation of the data and an increased design margin to attempt to accommodate unanticipated degradation. Extended life data will become available as components enter production. Programs to include CMCs in production should incorporate a plan to periodically pull components from service and test them to obtain the degraded properties. These properties are essential to the development of a fully validated life prediction model.

6.10.2.3 CMC Component Design and Development

Figure 6 shows a schematic of a CMC component design and development approach.

The eight steps outlined in Figure 6 are defined as: (i) candidate material systems are identified and conceptual designs are generated based on the environment, mission, and loads.

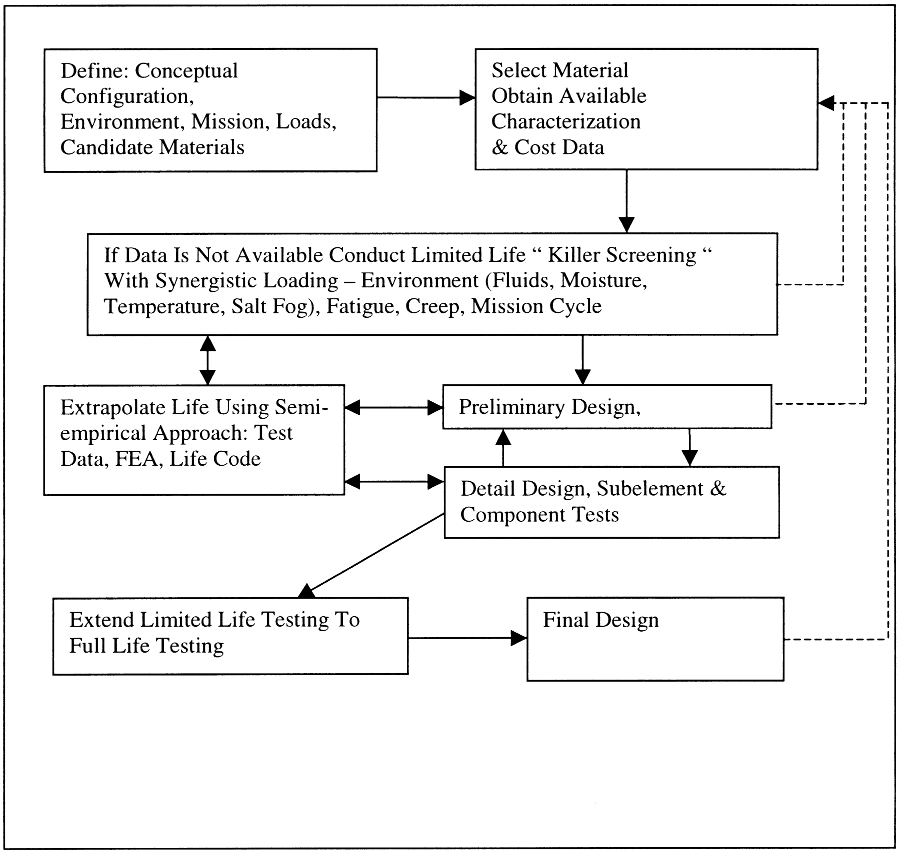

Figure 6 CMC component design and development approach.

Conceptual designs must consider the manufacturing and design constraints for each system, e.g., manufacturing quality, reproducibility, repairability, nondestructive evaluation (NDE), design property data, and cost should be considered in the conceptual stage. (ii) Material selection is based on the results of the conceptual studies. A thorough analysis of the available material property data is conducted and data shortfalls are identified. (iii) If critical material property data as identified by the "Killer Screening Tests" are not available, tests should be identified and conducted to obtain the critical data. These data would identify any "Achilles' Heels" in the material that would prevent its successful use in the intended application. It is imperative that these tests are conducted in a timely manner to prevent extended component development with the wrong material/design. Combined testing of loads, environment, and mission cycle are imperative as these combined effects act in a synergistic manner accelerating the rate of property degradation with time. (iv) An initial assessment of the component life is made using a semi-empirical approach with the existing data. The life assessment is continually updated, as data become available. These results provide data for a go/no-go decision on component development. (v) A preliminary design, including full FEA, is conducted. The component preliminary design and component load requirements are used to design subelements. A full FE analysis is performed on each subelement to assure that the stress state in the subelements is representative of the component stress state. These results are also used to identify strain-gage locations and to validate or calibrate the FE analysis by correlating the experimental and theoretical test results. Subelement tests representing the component environment and load conditions are conducted. The test results validate the design or indicate required modifications in the design. An iterative process between preliminary design and subelement testing is performed until a satisfactory design is achieved or a material revision is required. (vi) After successful completion of subelement testing, a detailed design is conducted along with subelement and component testing with representative loading and environment. (vii) The "Limited Life" testing initiated in the "Killer Screening Tests" is extended to "Full Life" testing. (viii) The final design is based on all the previous

Table 1 Long-term tests required to validate component life and develop life-prediction methodology.

A.	Initiate long-term environmental exposure and loading of material characterization panels and benchmark coupons at program inception and pull at selected intervals for residual-strength testing. Coupons with defects/damage should be included in the test matrix
B.	Define and perform accelerated mission testing, including defects/damage on panel coupons, benchmark (configuration shaped) coupons, subelements, and components
C.	Remove components at selected intervals from development engines for residual strength tests
D.	Remove components at selected intervals from flight engines for residual strength tests

data including the detail design data, "Killer Screening Tests" data, and the semiempirical life prediction results.

The development approach outlined is intended to assure some minimum limited life for the component with predictions for full life. Life past the limited life is based on extrapolations that must be validated through the "Full Life" testing. These data can be obtained by a combination of long-term material durability testing and periodic removal of components from service to determine the degree of property degradation. Periodic removal of components from service for residual strength testing is critical to validating the long-term durability of CMCs and developing/validating life prediction tools. Table 1 summarizes the long-term test requirements.

6.10.3 DESIGN REQUIREMENTS

Gas turbine engine components must be designed to withstand nonuniform, static, cyclic, and time-dependent mechanical and thermal loads. Components are designed to ultimate load, limit load, and cyclic load requirements. Limit loads are defined as the maximum expected loads encountered within the flight envelope on each flight. These loads define long-term requirements. Ultimate loads are obtained by applying a safety factor to limit loads. Design allowables for composites are typically greater for ultimate- load conditions than limit-load conditions due to the short duration of the ultimate-load condition. Time-at-load is especially important for CMCs due to its effect on accelerated degradation. Also, the requirements for sustaining ultimate-load conditions vary. Some conditions require that ultimate loads do not induce damage to the structure, whereas other less strigent requiremets may exist, such as: (i) the damaged structure must provide for a safe return to base, or (ii) be able to operate safely between a prescribed number of maintenace intervals assuring the damage will be found in time to repair or replace the component.

6.10.3.1 Static or Creep Loads—Mechanical, Thermal, Stress/Creep Rupture, Hot Streaks

Mechanical loads can be distributed pressure loads, local applied loads, or reactions. Limit load conditions which are of long duration can result in creep or stress rupture. Creep in CMC materials can result from fiber creep. Fiber creep rates vary significantly within the existing family of CMC fibers. Development of fibers generally results in a tradeoff of properties, e.g., higher creep rates may be traded for higher strength properties. The more prevelant pseudocreep phenomen generally observed in CMC materials is the result of accumulated matrix microcracking which results in a reduced modulus. This microcracking can result in increased environmental degradation, therefore, creep or stress rupture tests are essential to determining the long-term behavior of CMCs. This pseudocreep phenomenon can be introduced by thermal or mechanical loading. Thermal stress can be introduced by: (i) mechanically constraining the CMC from growing freely when subjected to a thermal load. Since CMC materials all have coefficients of thermal expansion which are significantly lower than those of metals, it is possible to introduce thermal stress in the CMC component if a thermally free attachment method is not used. Some thermally free attachment approaches will be defined in Section 6.10.6. (ii) Subjecting a component to a nonuniform thermal field. For example, in a gas turbine engine nozzle hot streaks can result from nonuniform combustion or cooling. In-plane thermal gradients will also occur when one component shields another from the hot gas path. Also severe through-thickness thermal gradients result in components which

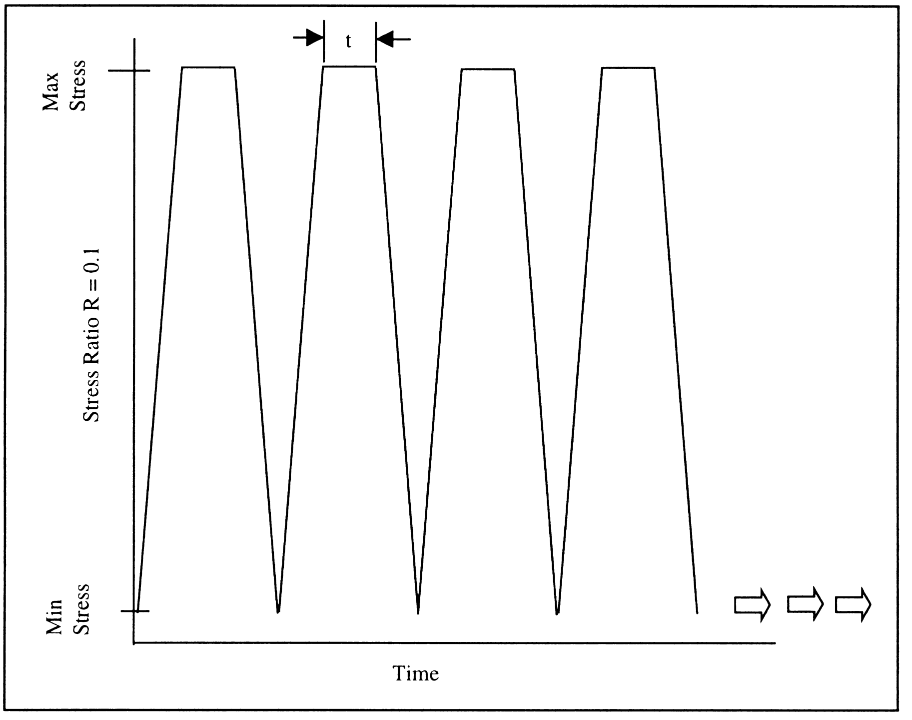

Figure 7 Low cycle fatigue.

are subjected to hot gas on the front surface and cooling air on the back surface. The through-thickness thermal gradients are generally more severe during a transient thermal condition prior to reaching steady-state conditions. These transient conditions can occur during takeoff or during the early stages of augmentor operation, such as when performing combat maneuvers.

6.10.3.2 Low Cycle Fatigue

Component fatigue occurs when components are subjected to cyclic mechanical or thermal loads. The key parameters quantified are number of cycles, cycle frequency, maximum stress, minimum stress, time at maximum or minimum stress, and stress-ratio (R). Stress-ratio denotes the ratio of maximum to minimum stress encountered in a cycle. Therefore, a negative stress ratio denotes the stress cycles between tension and compression in a cycle. A value of $R = -1$ denotes fully reversed stress where the peak tensile and compressive values are equal. A value of $R = 0.1$ denotes that the minimum stress encountered in a cycle is 10% of the maximum stress without cycling through zero stress. A negative stress ratio is generally a more severe condition for most composites than a positive stress ratio for the same absolute maximum stress value.

Low cycle fatigue (LCF) is a critical design condition for gas turbine engines representing such events as the number of flights performed in the expected lifetime of the component. For nozzle components the number of augmentor lights may be the key LCF driver for augmented gas turbine engines. The LCF conditions represented in Figure 7 show a hold time (t) at the maximum stress level. The life of a CMC component is influenced by the number of cycles encountered as well at the time at maximum load. For CMCs the time at maximum temperature is more detrimental to the life than the number of cycles. Also, the life is affected by the synergism between time, temperature, environment, and stress. Therefore, tests must be conducted which will evaluate these synergistic effects. Damage or cracks in the material affect the rate of material degradation. The rate of material degradation due to damage can be evaluated by precracking the test coupons prior to environmental testing.

6.10.3.3 High Cycle Fatigue

High cycle fatigue (HCF), as illustrated in Figure 8, is a critical design condition for gas turbine engines. Components are subjected to vibratory excitation induced by airflow on airfoils or the "white noise" acoustic environment

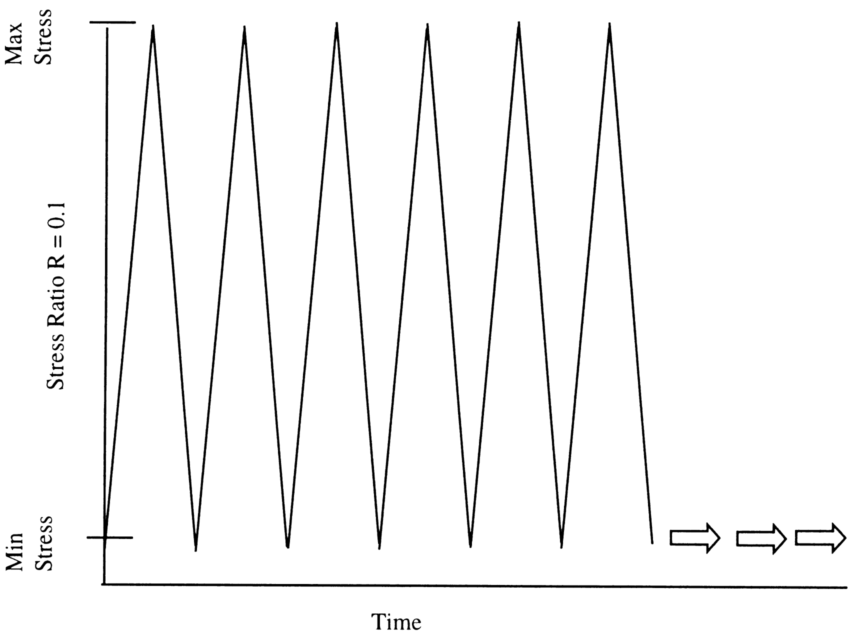

Figure 8 High cycle fatigue.

of nozzle components. Metals are typically assumed to have a fatigue "runout" condition, i.e., there is no further strength degradation after a given number of cycles, generally 10^7 or 10^8 cycles. CMCs cannot be assumed to have a runout condition since environmental degradation is a function of time. Therefore, ideally full-life testing is desired, but lacking these data the end-of-life strength is estimated based on degradation rates obtained from accelerated life tests. Eventually full-life testing is required to validate these assumptions. The life of a CMC component is influenced by the number of cycles encountered as well at the time at maximum load, although for CMCs the time at temperature is generally more detrimental to the life than the number of cycles. Also, the life is affected by the synergism between time, temperature, environment, and stress as defined above for LCF tests. The effects of material damage on HCF performance should be evaluated in a manner similar to that defined above for LCF material performance of damaged material.

6.10.3.4 Thermal Cycling

Gas turbine engines are subjected to thousands of thermal cycles during their lifetime. Although commercial aircraft gas turbine engines are designed to a greater number of hours of service than military aircraft gas turbine engines, their total number of thermal cycles are not necessarily greater than for military engines. Typically commercial aircraft engines are subjected to their most severe thermal environment, including thermal gradients, during takeoff, and then maintaining steady-state temperatures during cruise. Military engines are also subjected to severe thermal changes during takeoff, but their mission profile is not uniform and will result in severe thermal changes when the afterburners are ignited during combat, high-speed runs, or steep climbs. Typically, the most severe thermal design conditions result during a transient thermal condition, such as takeoff or afterburner ignition. These transient conditions result in severe nonlinear thermal gradients through the thickness of CMC structures, especially those with low thermal conductivity such as SiC/SiC composites. A homogeneous unconstrained flat plate when subjected to a linear temperature gradient through the thickness will have no thermal stress assuming a coefficient of thermal expansion independent of temperature and a uniform in-plane temperature distribution. The same plate when subjected to a nonlinear thermal gradient through the thickness will be subjected to thermal stress. Therefore, while an attachment design that allows free thermal bowing and in-plane growth minimizes thermal stress, a nonlinear thermal gradient as occurs in transient thermal conditions will result in thermal stress. If out-of-plane rotation of a plate subjected to a through-thickness thermal gradient is restrained at an attachment point the restraining moment will result in a thermal bending stress for both linear and nonlinear thermal gradients. Since through-thickness thermal gradient is a design driver in nozzle components such as cooling liners, flaps, and seals, it is important to approximate quickly the allowable thermal gradient to determine cooling requirements. A quick hand calculation can be performed to obtain an approximate allowable through-thickness thermal gradient for a given allowable in-plane stress by assuming a linear through-thickness thermal gradient and restrained out-of-plane rotation

$$\Delta T = 2\sigma / E\alpha$$

where σ = allowable stress, α = coefficient of thermal expansion, and E = Young's modulus.

6.10.3.5 Thermal–Mechanical Fatigue

Thermal–mechanical fatigue (TMF) combines thermal and mechanical loading. TMF is defined as in-phase when the thermal and mechanical loads occur at the same time and out-of-phase when the thermal and mechanical loads are independent of each other. Typically TMF testing is conducted both in-phase and out-of-phase to determine the criticality of each condition.

6.10.4 DESIGN CRITERIA

Two major structural design drivers for both commercial and military aircraft gas turbine engines are: (i) damage tolerance and (ii) durability. Strict requirements have been established for durable and damage tolerant designs by both military and civilian regulatory agencies such as the FAA and JAA. Safety-of-flight is the primary concern for both durability and damage tolerant designs, but durability of engine components is also driven by the financial risk to the manufacturer and the commercial or military customer. Damage tolerance design requires that any impact damage less than the established detectable threshold for the selected inspection procedure shall not reduce the strength capability below the ultimate load requirements. The design must be supported by appropriate analysis and test data.

6.10.4.1 Durability Requirements

Long-term life/durability tests must be conducted spanning the design service life (DSL) of the component. These tests must be initiated near or at the inception of the program unless the data is available from previous programs, since there are currently no validated life-prediction approaches for CMC materials. A long-term durability approach is outlined. It is essential that sufficient material (coupons, elements, subelements) be available at the initiation of the test program to ensure that coupons can be tested at predetermined intervals over the maximum anticipated design service life. Long-term durability testing should lead the in-service component application by a minimum of 2 years to assure that any unanticipated problems, such as excessive loss of structural properties with time and mission cycle, will be discovered in sufficient time to take corrective action and prevent in-service component failure. While this approach addresses safety-of-flight issues, it could still result in significant financial loss if a major problem is discovered during the warranted component life. This risk must be accounted for prior to committing to production. Although accelerated test methods have been proposed and numerous test methods have been used to determine mechanical property degradation with time, full validation requires full-term test data. The defined approach includes accelerated test methods that can be validated during the test program and then applied to life prediction of new components. The approach also includes removal and testing of components at selected intervals from developmental and flight engines. Table 1 summarizes the long-term life/durability approach and Figure 6 illustrates the desired outcome.

6.10.4.2 Damage Tolerance

Damage tolerance is a safety-of-flight issue and is the measurement of the ability of a component to perform its design function in the presence of a defect or damage. Therefore, a damaged component must have sufficient residual strength and stiffness to continue operating safely between scheduled maintenance/inspection intervals. If the damage occurs in a critical region that affects the safety-of-flight it must be repaired to full life capabilities or replaced. If the damage is undetectable the engine must be able to operate safely to full life or a prescribed number of maintenance intervals after the damage grows to a detectable level.

Sources of damage to aircraft and gas turbine engines are illustrated in Figure 9. Damage due to manufacturing defects, tool drop, handling, installation, and engine maintenance are of primary concern for CMC components in gas turbine engines. The ability of nondestructive evaluation (NDE) to detect defects or damage is a major design consideration, since the design considerations for detectable and undetectable

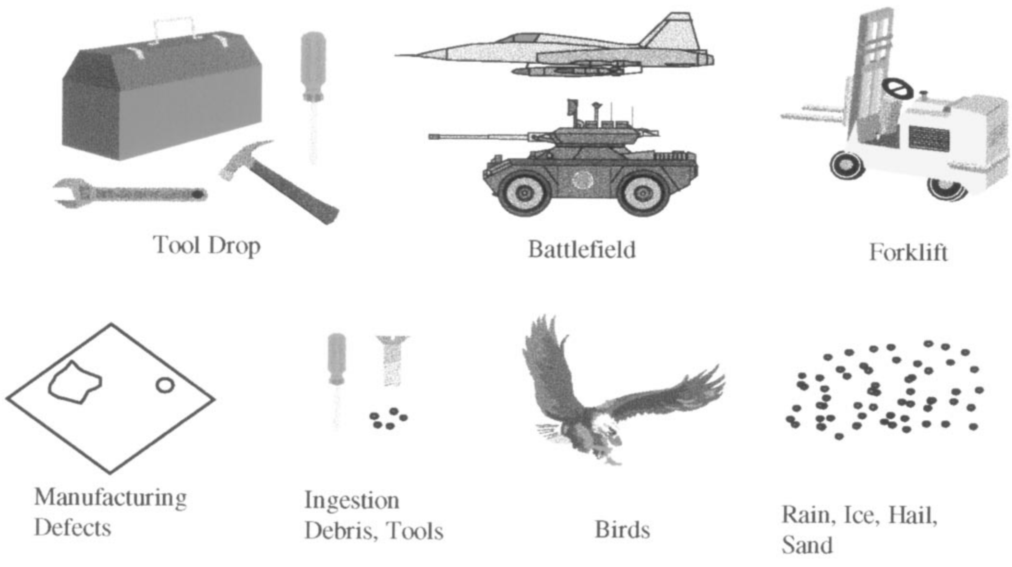

Figure 9 Sources of damage.

damage are different as defined below. Damage in CMC components can accelerate the rate of environment induced property degradation.

Three critical issues associated with damage tolerant design are: (i) detection of fabrication defects or damage induced during service, (ii) prediction of the growth rate of the damaged region, primarily delamination, and the effect on the structural performance/life of the component, and (iii) validation of repairs. Service induced damage as illustrated in Figure 9 includes: (i) handling damage and impact damage due to dropped toolboxes, (ii) runway debris, (iii) sand, (iv) rain, (v) hail, (vi) ice, and (vii) birds.

6.10.5 DATA REQUIREMENTS

Design of CMC components to meet long-term durability requirements for aircraft gas turbine engines requires an extensive database. These data must be representative of the environment and loads encountered in the engine mission cycle to design a component to meet long-term durability and damage requirements. These effects must be evaluated in a synergistic manner, as degradation is more rapid when the loads and environment are combined in the material characterization tests to represent actual mission conditions.

A major design consideration for CMCs is the reduction or change in material properties due to microcracking and environmental degradation. CMCs generally exhibit microcracking at less than 100 MPa tensile stress. Key properties affected by environmental degradation are strength, modulus, thermal conductivity, and thermal expansion. Environmental degradation of strength and stiffness have been more thoroughly evaluated than environmental degradation of thermal conductivity and expansion. Often the effects of environmental degradation on conductivity and expansion are neglected or relegated to a secondary role in evaluation of material properties required for design. Changes in conductivity can alter significantly the transient thermal distribution in components such as nozzle liners where the critical design condition is often the thermal stress generated by transient thermal loads. Therefore, thermal conductivity and thermal expansion, in addition to strength and modulus properties, must be evaluated for the mission life of the component to be included in the "end-of-life" allowables determination.

Long-term durability tests must include open-hole coupons to evaluate the effects of stress-concentration factors around open holes. Composite materials have shown a dependence of stress-concentration factors on hole diameter for fast-fracture tests. Smaller diameter holes have lower stress-concentration factors since the region of peak stress around the hole is less for smaller hole diameters. There is currently a lack of data to evaluate fully the effects of stress concentrations around holes on the long-term durability of CMCs. The localized damage near the surface of the hole which reduces the stress-concentration effects in fast-fracture tests is a region of accelerated property degradation in long-term durability tests. The degradation rate is affected by the initial hole size, i.e., less degradation for smaller holes. Therefore, for components that have cooling holes or attachment holes, it is imperative that

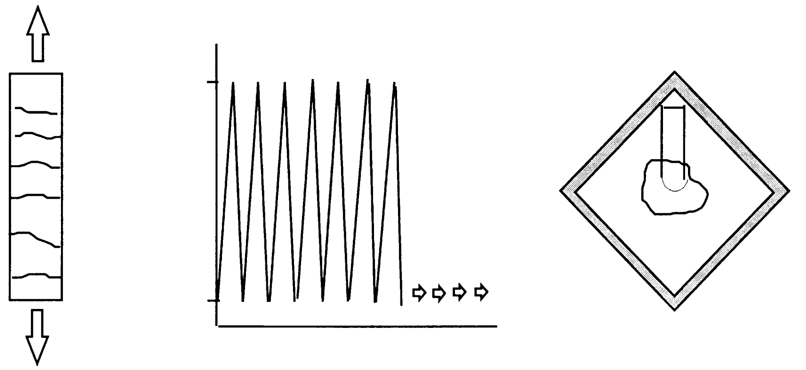

Figure 10 Damage induced prior to environmental exposure.

long-term durability tests include coupons with open holes representative of those in the actual component.

An early assessment of material performance can be obtained from specialty rigs simulating regions of an engine, such as nozzles, combustors, or turbines. More generic "Killer Tests" are defined in the following section.

6.10.5.1 "Killer Tests"

Because of the lack of maturity of CMCs it is imperative that material behavior be established at the inception of design. These key data are obtained from "Killer Tests" as proposed in Miller (1999). "Killer Tests" are tests defined to subject CMCs to the most critical environmental and load conditions anticipated for the material application. These data should be available at the inception of the design or evaluated during the conceptual or preliminary design phase. The objective of the tests is to determine any "Achilles' Heels" in the material prior to any significant financial or time investment in the design. These tests must include the combined effects of environmental exposure (temperature, salt-fog, moisture, fluids) with loads (static, cyclic, creep) and predamage (impact, handling, maintenance). The combined effects of environment, stress, and damage can greatly accelerate the rate of degradation of CMCs. Standard "Killer Tests" are defined which include these combined effects, but for a particular design the actual mission cycle can be used to define a set of critical "Killer Tests" to be executed in the early phases of the design. These tests are not intended to provide statistically validated final design allowables, but rather to provide data for preliminary design. These data can be included in the full material characterization test matrix required to determine statistically derived final design allowables.

The "Killer Tests" described in the following sections provide a guide to the generic type of data a material vendor should provide to a designer such that the material can be evaluated in the conceptual or preliminary design phase. If all the data for the "Killer Test" are not available at the inception of the design of a particular component, the mission cycle for the particular component must be used to define which critical data are missing. A test plan, including cost, to obtain these data must then be developed to determine if it is worth proceeding with the design.

6.10.5.1.1 Environmental conditioning and precracking

Material characterization must be conducted on environmentally conditioned coupons that reflect the mission environment for the intended application. Moisture, rain, salt, fog, and various fluids (cleaning fluids, oil, etc.) are typical of the environments that must be included in the environmental degradation evaluation of CMC materials. Conditioning can occur at discrete intervals in the durability tests or the durability tests can be run in environmental chambers. The latter is more severe, but it is also more expensive and the availability of test facilities is limited, therefore, the former is more widely used. The mission cycle should be used to give guidance on the applicability of a particular method.

It is imperative that CMC material characterization includes material with initial precracks or damage. Tests should also include open hole coupons. Methods of inducing damage prior to environmental testing are illustrated in Figure 10. Damage can be induced by: (i) fatigue loading where the test coupon is loaded to a stress above the proportional limit or initial cracking stress, e.g., stress to 120% of the proportional limit or cracking stress; (ii)

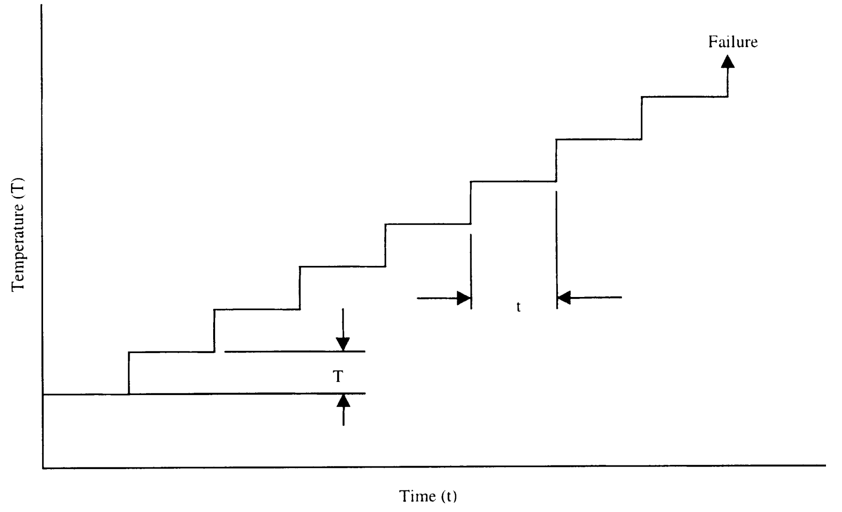

Figure 11 Step-temperature creep test at constant stress.

impact loading which should consist of barely visible damage that could be missed during a routine inspection, and a second more severe level representative of damage that could occur between inspection intervals; (iii) static loads where the test coupon is stressed above the proportional limit prior to initiating the durability testing, e.g., stress to 120% of the proportional limit or cracking stress. The durability tests should include stressing above the matrix cracking stress at prescribed intervals during the test to determine any effects on degradation rates. These periodic overstress tests are required to assess the long-term performance of CMCs since CMCs may contain self-healing mechanisms that can be depleted by repeated overstressing above the microcracking stress level.

6.10.5.1.2 Loads

The type of loads applied in the durability testing of CMCs is a critical part of the evaluation of a CMC material for a particular application. These include static and cyclic application of thermal and mechanical loads. When available the mission cycle should be used as a guideline for establishing the most cost-effective tests for a particular application.

The synergistic degradation effects of time, load, and environment should be evaluated initially using stress rupture or creep tests. Accelerated test methods where the stress and temperature are incrementally increased over time are defined. These step-stress and step-temperature creep tests provide essential data to evaluate rapidly the relationship between stress, temperature, and environmental degradation.

LCF, HCF, and combined thermal and mechanical fatigue (TMF) tests with environmental conditioning and damage provide critical data for the durability evaluation of CMCs. Time at maximum stress is a more critical measurement of material degradation at elevated temperatures ($>800\,^{\circ}$F) than the number of stress cycles. Therefore, LCF that includes hold time at maximum stress as shown in Figure 7 generally represents a more critical test than a HCF test. The increased severity of the LCF test is the result of increased environmental degradation under stressed conditions at elevated temperatures.

Fatigue tests should be interrupted at predetermined intervals during the test to measure residual properties and perform NDE. Modulus, thermal conductivity, thermal expansion, emissivity, and dielectric property measurements can be obtained without damaging the coupon. Weight measurements along with standard NDE procedures can also be performed. Sufficient samples should be included in the testing to permit residual strength tests to be performed at predetermined intervals. Residual property tests provide essential data to determine the degree of property degradation and they provide the basis to determine the end-of-life allowables required for design.

6.10.5.1.3 Step-temperature creep test at constant stress

The step-temperature creep tests, illustrated in Figure 11, provide essential data required for evaluation of the relationship between stress, temperature, and environmental degradation. A significant understanding of the relationship between degradation and temperature is obtained from a single specimen by stepping the temperature after discrete intervals of time. These data are required to determine the maximum use temperature or if there is an intermediate temperature at which the properties of CMCs are degraded. Most CMCs have shown a local minimum in properties between approximately 1000 °F and 1200 °F. The data from the step-temperature creep tests are used in defining the temperature levels for the step-stress creep tests at constant temperature defined in the next section.

The step-temperature creep test is ideal for screening new materials, determining relative comparisons between materials, and determining design stress limits for materials. The load–deflection curve should be recorded over the life of the test to determine any changes in creep rates as the temperature is stepped up until material failure occurs. In addition, a load–deflection curve should be recorded at the beginning and end of each temperature step. Changes in the slope of the load–deflection curves and/or weight measurements are used in the evaluation of material degradation effects.

The recommended temperature for the initial temperature step is 900 °F with incremental steps of 100 °F up to 1300 °F to determine if a local minimum exists. The incremental steps are then increased to 200 °F until failure occurs. In addition to identifying any intermediate temperatures of concern, this test rapidly evaluates the synergistic effects of stress, temperature, and environment on the degradation of CMC materials. Changes in the load–deflection curves and/or weight measurements are used in the evaluation of material degradation effects.

6.10.5.1.4 Step-stress creep test at constant temperature

A significant understanding of the relationship between degradation and stress is obtained from a single specimen by stepping the stress after discrete intervals of time as illustrated in Figure 12. These data, along with the data from the step-temperature creep test at constant stress, are used to define the stress levels for the constant-temperature stress rupture tests.

The load–deflection curve should be recorded over the life of the test to determine any changes in creep rates as the load is stepped up to failure. In addition, a load–deflection curve should be recorded at the beginning and end of each load step. The recommended stress for the initial stress step is the lower of either the limit design stress, or 50% of the proportional limit. The recommended step stress increment is 25% of the proportional limit. Tests can be conducted in air: (i) without moisture conditioning, (ii) moisture condition between each load step, or (iii) conduct tests in a moisture chamber. The first approach is the least expensive and yields results on the interactive effects of stress and oxidation. The second approach with moisture conditioning between steps combines the synergistic degradation effects of time, environment, and load. This approach will determine quickly if moisture is a major contributor to property degradation as has been shown for a number of CMC materials. Often the inhibitors added to reduce oxidation in air increase the effects of moisture on property degradation. The latter is the most severe condition and the most expensive where moisture can be introduced under load. These tests rapidly evaluate the synergistic effects of stress, temperature, and environment on the degradation of CMC materials. Changes in the slope of the load–deflection curves and/or weight measurements are used in the evaluation of material degradation effects.

The test shown in Figure 12 can be modified to evaluate the stress rupture life at a constant stress by eliminating the stress increase at the intervals shown. These tests should also be interrupted at predetermined intervals for moisture conditioning and the application of matrix cracking overstress. If the specimen reaches the required life without failure there are several options for continued evaluation: (i) perform NDE and measure residual properties prior to sectioning coupons for further assessment of damage; (ii) perform NDE and then a fast fracture test to obtain residual strength; (iii) perform NDE and continue the stress rupture test at an increased stress or temperature level. Repeat this procedure until failure occurs. If evaluations are being conducted for a specific component for a given mission profile it is possible to modify the test shown in Figure 12 to match the mission profile conditions for time, stress, and temperature.

6.10.5.1.5 Low cycle fatigue test

LCF as illustrated in Figure 7 is a critical design condition for gas turbine engines. LCF represents such events as the number of flights performed in the expected lifetime of the component. For nozzle components the number of augmentor lights may be the key LCF driver for augmented gas turbine engines.

The life of a CMC component is influenced by the number of cycles encountered as well as the time at maximum load. The time at maximum temperature is more detrimental to

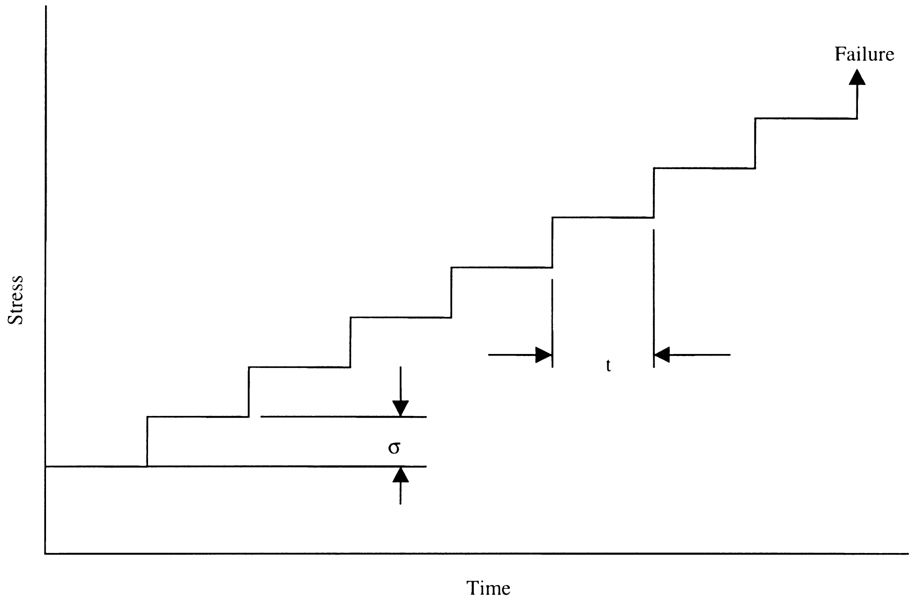

Figure 12 Step-stress creep test at constant temperature.

the life of a CMC component than the number of cycles over a given time span. Also, the component life is affected by the synergism between time, temperature, environment, and stress. Therefore, test conditions should include time, temperature, and moisture (humidity, salt-fog) conditioning. Also, damage or cracks in the material affect the rate of material degradation. This degradation effect can be evaluated by precracking the coupon. Prior to moisture conditioning at the initiation of each repetition of *N* cycles, as illustrated in Figure 13, an overstress above microcracking should be applied to the coupon. An overstress of at least 20% is recommended. This is representative of an inadvertent overload due to impact, handling, and ultimate load conditions which can occur in service. These overstress tests are required to assess the long-term performance of CMCs since CMCs may contain self-healing mechanisms that can be depleted by repeated stressing above the microcracking stress level. As a minimum, stress–strain or load–deflection curves should be recorded at the beginning and end of each series of *N* stress cycles to determine any changes in material behavior. Sample weights should also be obtained at the beginning and end of each repetition of *N* cycles as a part of the material degradation assessment. Requirements for additional nondestructive property evaluation as defined in Section 6.10.5.1.2 should be assessed based on the intended application of the material.

Cyclic tests can be run continuously in environmental chambers or tests can be interrupted at discrete interval to environmentally condition the coupons and re-apply the matrix cracking stress. Cyclic tests should be conducted with sufficient samples to permit removal of samples at selected intervals to obtain residual strength values. These tests provide essential data on the degradation rates and are also required in the development/validation of life prediction methods.

The step LCF stress test shown in Figure 14 is ideal for screening new materials, determining relative comparisons between materials, and obtaining design stress limits for materials. The recommended maximum stress for the initial series of *N*-LCF cycles is the lower of the limit LCF design stress or 50% of the proportional limit. The recommend load steps after each series of *N* cycles are 20% of the initial LCF load.

6.10.5.1.6 High cycle fatigue test

HCF as illustrated in Figure 8 is a critical design condition for gas turbine engines. Components are subjected to vibratory excitation induced by airflow on airfoils or the "white noise" acoustic environment of nozzle components. Metals are typically assumed to have a fatigue "runout" condition, i.e., there is no further strength degradation after a given number of cycles, generally 10^7 or 10^8 cycles. CMCs cannot be assumed to have a runout condition since environmental degradation is time dependent. Therefore, ideally full life testing is desired, but lacking these data the end-of-life

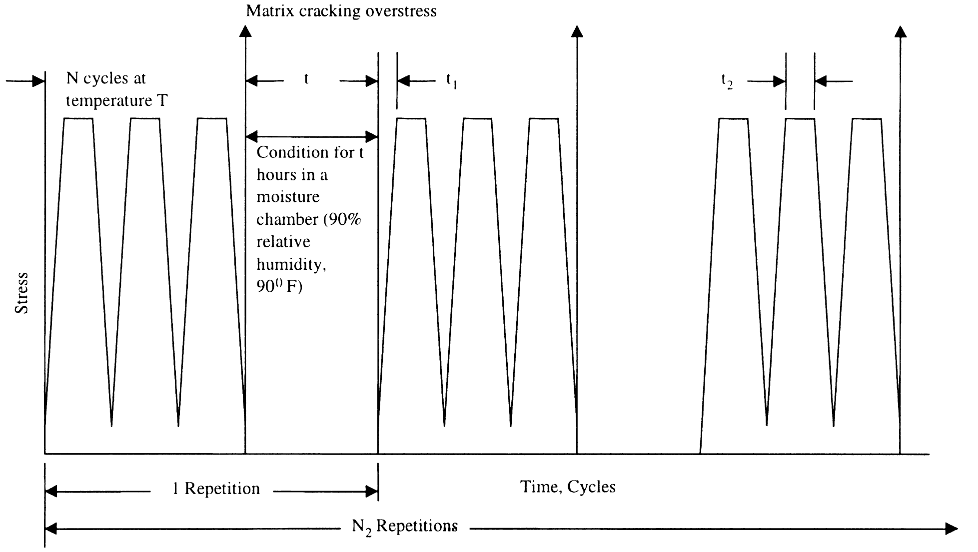

Figure 13 Interrupted LCF tests.

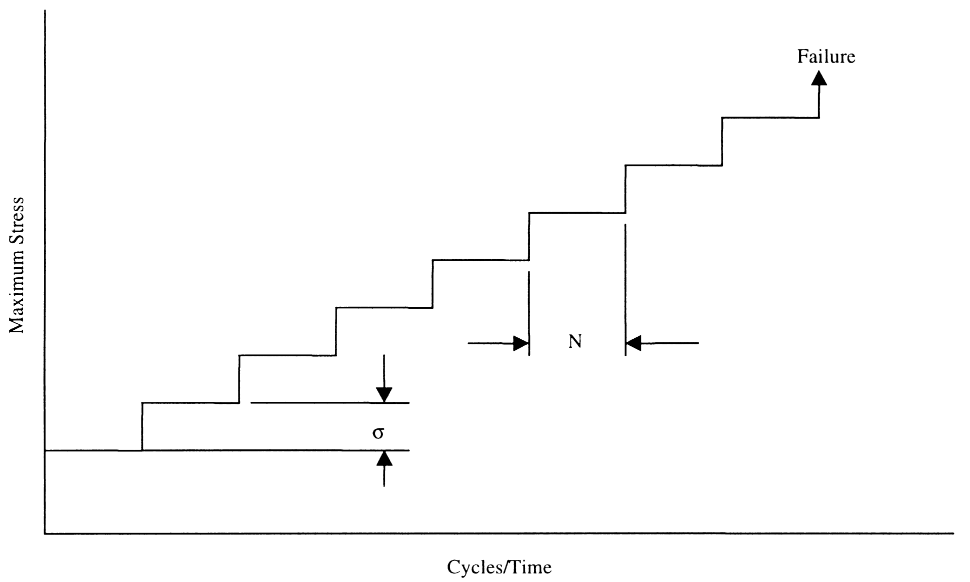

Figure 14 Step LCF test.

properties are estimated based on degradation rates obtained from accelerated life tests. Eventually full life testing is required to validate these assumptions. The life of a CMC component is influenced by the number of cycles encountered as well at the time at maximum load. The same general procedure is followed for HCF testing as was described for LCF testing, except that (i) dwell time at maximum stress is kept at a minimum, (ii) cycle test frequency is increased for HCF, and (iii) the total number of cycles is increased significantly. The requirements for moisture conditioning, precracking, and stress overload are essentially the same for HCF and LCF testing. Since time at maximum stress and temperature are key contributors to accelerated degradation rates, HCF testing has a lower priority in the "Killer Test" matrix than stress rupture or LCF tests.

6.10.5.2 Configuration Shaped Coupons

Figure 15(a)–(c) show configuration shaped material characterization coupons which are essential for determining initial strengths of coupons which realistically include processing effects encountered in typical structures. These

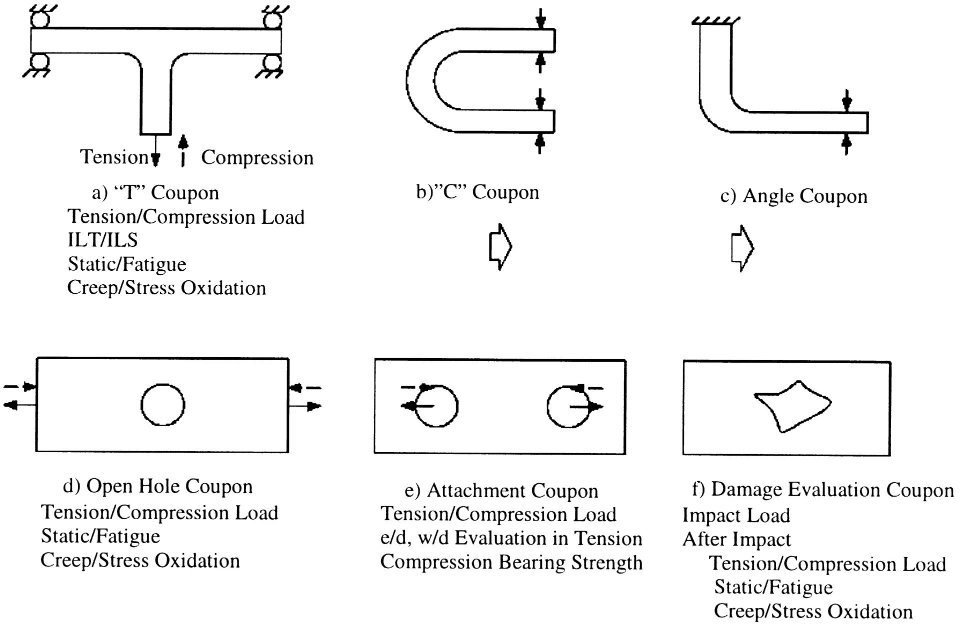

Figure 15 Configuration shaped coupons.

coupons do not replace the standard material characterization coupons but provide complimentary data. The standard material characterization coupons are essential but they generally represent nonconservative design allowables since flat panels represent the highest quality fabrication methods. Fiber distortion, crimping, etc. are minimized and uniform fabrication pressures and temperatures are achieved more easily in flat panels than in most component configurations. The configuration shaped coupon tests illustrated bridge the gap between the standard material characterization tests and subelement tests.These data can be used to compare competing processing methods as well as guide the development or improvement of processing methods. Detailed finite element analyses of these coupons provide the full 3-D stress–strain state at failure. These results are used to determine the design allowables achieved in a configuration that may more realistically represent the critical regions of the structure. These allowables are used in the FEA of the actual structure in regions represented by these shapes. These data are essential to the designer in all stages of design to minimize development cost and reduce risk. These data are especially critical for curved or rib-stiffened panels as interlaminar shear and tension are critical failure modes, and these are the properties that are likely to be reduced significantly from the flat laminate values. Residual fabrication stresses are a major factor in the reduction of these strength properties compared to flat laminate values.

The configuration shaped coupon tests can also be used to benchmark fabrication methods. When pulled in tension or compression these configuration shaped coupons are subjected to realistic multiaxial stresses including interlaminar tension/compression, interlaminar shear, and in-plane tension/compression. By varying the specimen dimensions or support points the multiaxial stress ratio can be varied. These data are also applicable to the development of multiaxial failure criteria for CMCs. Although coupon procurement costs and test setup are higher than for standard flat coupons, the tests are relatively inexpensive compared to in-plane biaxial test or general subelement tests.

Figure 15(d)–(f) represent typical tests that are required to provide design allowables for attachments, cutouts, and impact. These data supplement the data generated by the "Killer Tests" defined in Section 6.10.5.1.

6.10.5.3 Composite "T" Subelements with Interlaminar Cracks

The strength properties of composite materials are anisotropic since they rely on the fibers to provide the primary load carrying capability. For laminated composites the in-plane properties are generally more than an order of magnitude greater than the out-of-plane properties. Therefore, optimally designed composites orient fibers in the principal load-carrying directions. Even utilizing this concept, a large percentage of composite components fail due

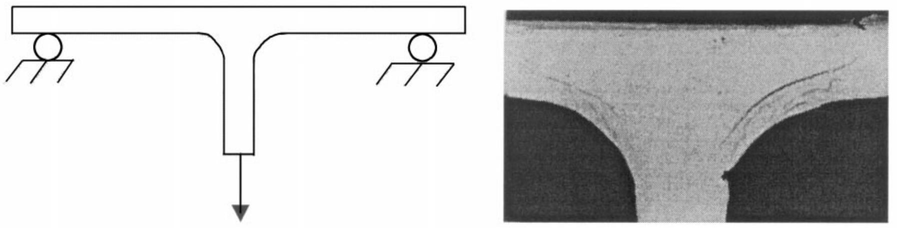

Figure 16 Composite "T" subelements with interlaminar cracks.

to the secondary interlaminar stresses as a result of the relatively low interlaminar strength of CMC materials. Also, for composites that are processed at elevated temperatures, the residual processing stresses significantly affect the load carrying capability of a structure. Since these residual stresses are highly dependent on the shape of the component fabricated, the design allowables should be obtained from benchmark coupon tests closely resembling the configuration of the actual component as defined in Section 6.10.5.2. Therefore, for rib (blade) stiffened structures the "T" coupon is ideal for obtaining interlaminar design allowables. A three-point "T" test along with a photomicrograph of the failed coupon is illustrated in Figure 16. The failure mechanism is interlaminar tension combined with interlaminar shear. The relatively low load carrying capability of a rib stiffened laminated composite structure is demonstrated by this test for loading conditions where a tensile load must be transferred from the ribs to the face-sheet. This type of load can occur due to (i) pressurized cooling flow, (ii) thermal gradients through the liner, (iii) thermal distortion of the backstructure, or (iv) acoustic loading.

Although Figure 16 illustrates a still photograph of the damaged specimen, real-time failure progression can be recorded on video. Video recording permits a study of failure progression under a realistic multiaxial stress state. Recordings of failure progression or crack growth under fast-fracture, fatigue, or stress rupture are useful for improving designs and developing failure and life prediction models.

6.10.6 ATTACHMENTS

Attachment regions of PMCs and CMCs are generally recognized as the most difficult and important design challenge. The low matrix or interfiber strength of these composites limits the ability to transfer load through shear. Interlaminar shear and interlaminar tension stresses are recognized as key design drivers in attachment regions where large shear and bending discontinuity loads occur. These loads often result in the requirement for complex attachment designs that can contribute significantly to an increase in component weight and/or decrease in durability. Typically attachments contribute significantly to the component development cost, as subelement tests of the attachments generally are required for component validation or certification. The attachment design challenge is significantly more difficult for CMCs than for PMCs. CMCs have lower interlaminar strengths than PMCs and CMC components operate at higher temperatures than PMC components. The high operating temperatures can result in excessive thermal stress if the composite to metal attachment is not designed to account for the low coefficient of thermal expansion of the CMC relative to metal. The high operating temperatures of CMCs preclude the use of metal fasteners in regions approaching the maximum operating temperature of CMCs. Therefore, the attachments must be confined to regions not exceeding the capability of metal fasteners, or composite fasteners must be used. Both of these approaches have been successfully applied to CMC component attachments.

6.10.6.1 Thermally Free Attachment Designs

Figure 4 illustrates typical rectangular and axisymmetric exhaust nozzles for augmented gas turbine engines. Metal nozzle components that are in the hot-gas flow-path cannot withstand the extreme gas temperatures without the use of cooling air. The requirement for cooling air increases the complexity of the design as well as reducing engine performance. High temperature CMCs offer potential to operate as structural components at higher temperatures than metals. Therefore, use of CMCs can reduce or eliminate the need for cooling air. CMCs can be used in the hot gas path with metal back-structures as the primary load members operating at reduced temperatures. Use of CMCs to shield the metal structure introduces a significant design challenge presented by the difference in

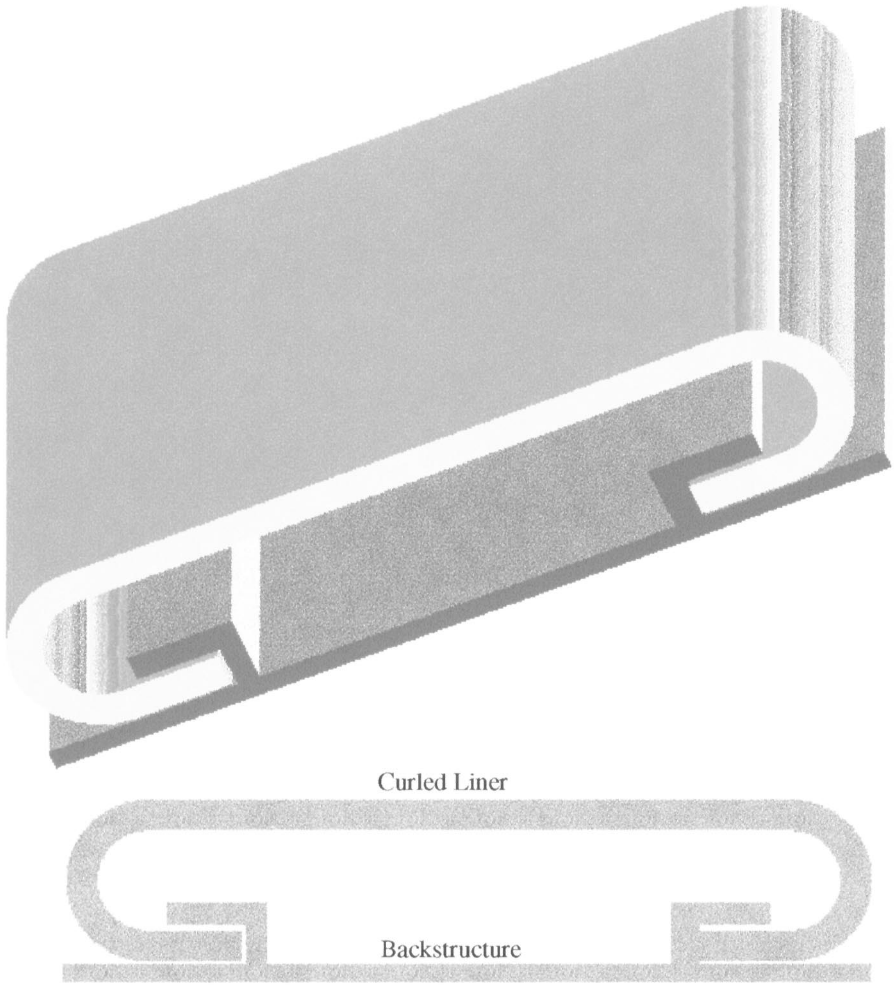

Figure 17 Curled liner.

thermal growth of CMC and metal components. A number of "thermally free" attachment concepts, as illustrated in the following sections, have been developed to address the thermal growth mismatch between CMC and metal components.

6.10.6.2 Thermally Free Curled Liner

The curled liner concept illustrated in Figure 17 uses high temperature composite curled liners to protect the metal back-structure of an exhaust nozzle from the hot exhaust gas. Cooling air flows between the composite liner and the metal back-structure to maintain the metal temperature within its operational limits. The curled liner slides over the metal back-structure and is retained at one end allowing free lengthwise thermal expansion between the metal back-structure and the CMC liner. If the design permits, the liner could be constrained at its mid-point. Constraining the liner at the mid-point would reduce the thermal growth from the constrained point by half, which would reduce any frictional loads at the attachment. Allowing a predetermined gap between the CMC liner and the metal substructure permits free thermal growth across the width. The cooling air flowing under the composite liner can subject the liner to a significant pressure load. The pressure load can induce significant interlaminar tensile and shear stresses in the radius region. Also, even though the liner is allowed to grow freely in-plane, the thermal gradient through the thickness of the liner will result in out-of-plane bowing, which results in both interlaminar and in-plane stresses. The metal back-structure supporting the composite liner is also subjected to a through-thickness thermal gradient. The resulting distortion of the metal back-structure will induce loads into the composite liner. These loads must be accounted for when determining the state of stress in the composite liner.

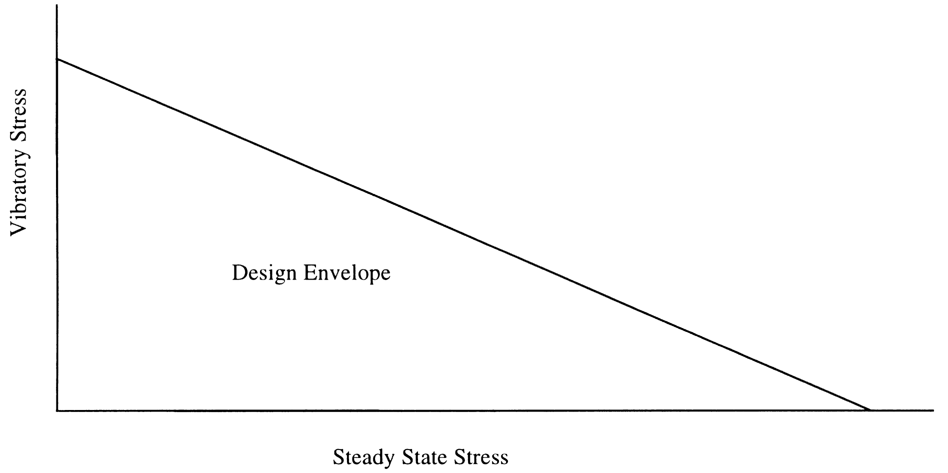

Figure 18 Goodman diagram.

The interlaminar tensile stress in the radius region is the critical design driver. The width and thickness of a liner is primarily driven by the pressure, thermal gradient, and interlaminar tensile strength of the CMC. Also, the vibratory stresses resulting from severe acoustic environments must be evaluated and included in the final determination of design margins. An interactive failure criterion is used to combine the steady-state stresses and the vibratory stresses. One such interactive failure criterion is the Goodman diagram shown in Figure 18. The steady-state stress is plotted along the horizontal axis and the vibratory stress is plotted along the vertical axis. The design margin is positive when the design stresses fall within the triangular area in Figure 18.

Under excessive acoustic, pressure, and thermal gradient loads, delamination will initiate in the radius region. After the initial delamination reaches a critical length it will stabilize and an increase in loads will result in additional delamination at adjacent layer interfaces. The failure mechanism is graceful rather than catastrophic, but environmental degradation of material properties will accelerate in regions of delamination. If delamination results from an ultimate load condition it must be determined if the liner is to survive limit loads until detected at a scheduled maintenance interval. This capability would permit the use of less conservatism in the design.

6.10.6.3 Thermally Free Flat Liner

The flat liner concept illustrated in Figure 19 is attached to the nozzle back-structure with bolts. As in the curled liner concept, cooling air flows between the composite liners and the metal back-structure to maintain the metal temperature within its operational limits. The attachment concept illustrated permits thermally free in-plane growth without rotation or chattering. The flat composite liners are attached to the metal back-structure using metal bolts. The bolts are also recessed within the liners to maintain a uniform surface and to shield them from the hot exhaust gas flow. Thermal barrier coatings can be applied to the bolts or cooling air can be provided to maintain the maximum bolt temperature within its design allowable. The composite liners are supported on metal ribs that form part of the back-structure. A tight fit is provided at one fastener as illustrated by the fixed point. When isotropic thermal growth exists it is possible to permit free in-plane thermal growth by slotting all remaining holes along radial lines intersecting the center of the fixed hole. The assumption of isotropic in-plane expansion coefficients is reasonable for a laminate with any combination of 0, 90, +45, −45 plies of balanced fabric. The length of each "racetrack" slot is determined by the magnitude of the differential thermal growth between the metal back-structure and the composite liner measured from the fixed hole to each slotted hole. As the metal back-structure expands, the bolts are free to slide against the composite surface. The only restraint to in-plane growth results from the friction force between the metal bolt and the composite liner. The flat liner is designed to the same loads as defined for the curled liner, but the critical failure modes are different. The critical shear and bending loads occur at the bolted attachment locations.

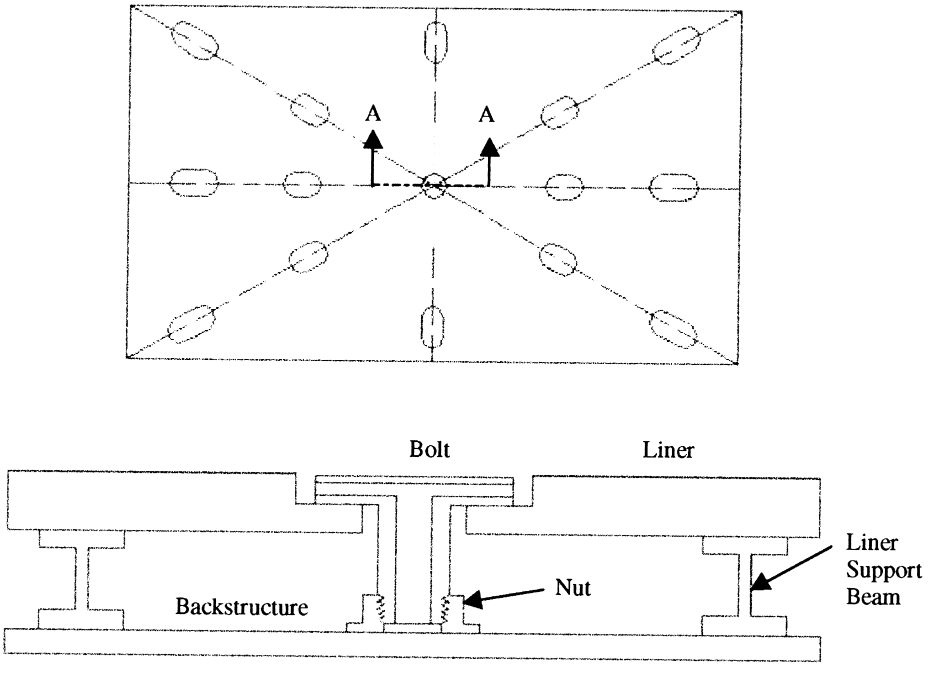

Figure 19 Flat liner.

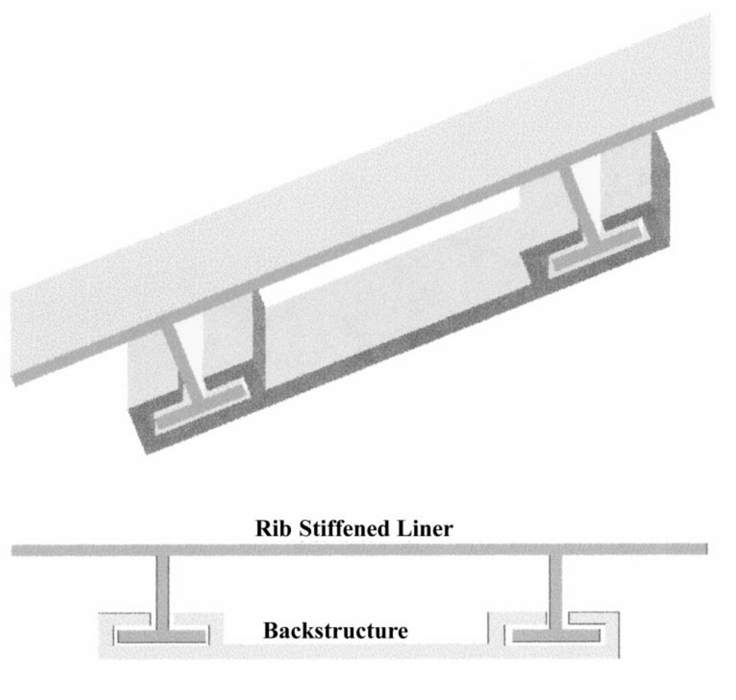

Figure 20 Rib-stiffened.

6.10.6.4 Rib-stiffened Liners

The rib-stiffened liner concept illustrated in Figure 20 is attached to the back-structure through its "T" stiffeners. The "T" stiffeners, supported in metal tracks, provide a "thermally free" attachment that allows the metal back-structure to expand in-plane, minimizing thermal stress on the composite liners. The liner can slide freely in the track in the axial direction. Sufficient gap is provided in the transverse direction between the "T" and the track to account for any thermal growth mismatch between the metal back-structure and the com-

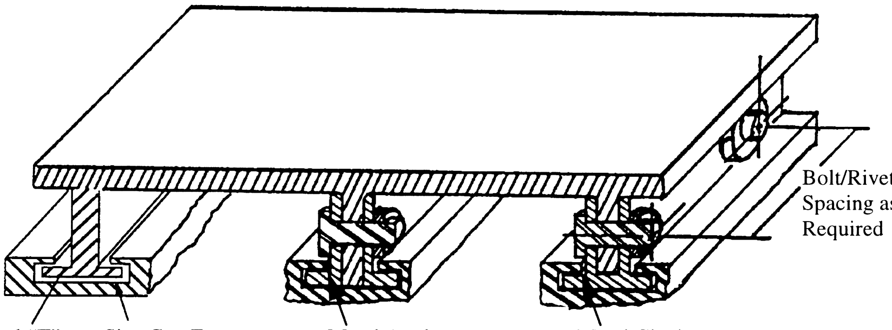

Figure 21 Thermally free "T" attachment concepts.

posite liner. The liners are retained in a manner similar to that described for the curled liners. The liners are retained at one end allowing free lengthwise thermal expansion between the metal back-structure and the CMC liner. If the design permits, the liner could be constrained at its mid-point. Constraining the liner at the mid-point would reduce the thermal growth from the constrained point by half which would reduce any frictional loads at the attachment. Free thermal growth across the width is permitted by allowing a predetermined gap between the width of the CMC "T" and the metal track. The required gap increases linearly with distance from the constrained point. Therefore, lateral constraint of the center stiffener is the preferred design approach.

The liner is assembled on to the back-structure by sliding it into the metal tracks. If the liner ribs are scalloped, and cutouts are provided in the metal tracks, the liner can be assembled from above. The scalloped liner is positioned in the cutouts in the metal track and clocked forward until the "Ts" are retained in the metal track.

Under excessive acoustic, pressure, and thermal gradient loads, delamination will initiate in the radius region where the rib intersects the face-sheet or the "T" cap. After the initial delamination reaches a critical length it will stabilize and an increase in load will result in additional delamination at adjacent layer interfaces as illustrated in Figure 16. As defined for the curled liner, the failure mechanism is graceful rather than catastrophic, but environmental degradation of material properties will accelerate in regions of delamination. If delamination results from an ultimate load condition it must be determined if the liner is to survive limit loads until detected at a scheduled maintenance interval. This capability would permit the use of less conservatism in the design.

Several thermally free "T" attachment designs are illustrated in Figure 21. Three basic "T" attachments are illustrated. The integral "T" has the "T" fabricated as part of the composite liner. The second has two metal angle sections bolted directly to the composite rib to form a metal "T." The last shows a metal clevis attached to the composite rib. The disadvantage of the integral "T" is that it is subject to interlaminar failure in the radius region of the "T." The latter two eliminate this failure mode and the load is transferred from the composite rib to the metal "T" using standard composite bolted joint technology which utilizes the high in-plane strength of the composite to transfer the load. When the critical failure mode at the "T" attachment point is eliminated, the critical design driver becomes the interlaminar stresses at the intersection of the stiffener to the face sheet. These interlaminar stresses result from the same loading conditions identified for the curled liners The interlaminar failure mode resulting from these loads is illustrated in Figure 16.

6.10.6.5 Composite Fastener Design

Considerable effort has been expended on the attempted development of high temperature composite threaded bolts over the last two decades. Successful development has been primarily limited to lightly loaded bolts. These attempts have included laminated two-dimensional (2-D) as well as multidirectional reinforced bolts. The basic problem with threaded composite bolts is that the load is transferred from the nut to the bolt shank through shear in the threads. This shear load results in significant matrix or interlaminar shear in the composite that is the weak link in CMC materials. Therefore, the ability to transfer load from the

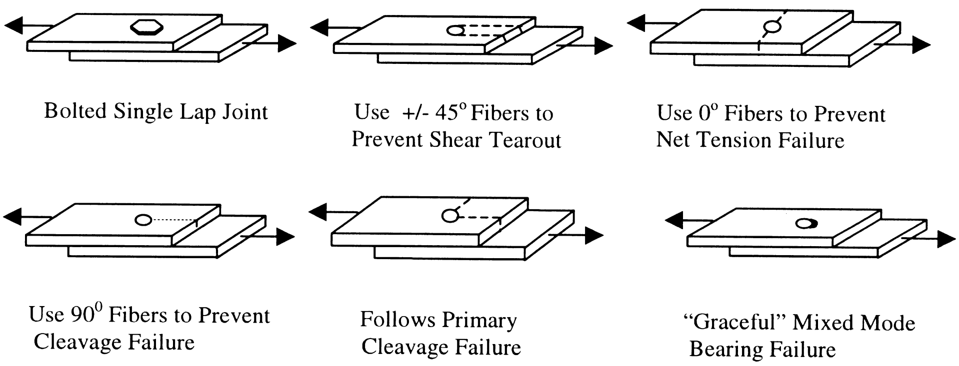

Figure 22 Bolted lap joint technology applied to fastener design.

nut to the bolt is significantly limited. Another weak link in composite bolts is the ability to transfer load from the bolt head to the shank of the bolt where the load must again be transmitted by shear. Neither the two-dimensional or multidirectional laminates result in fiber orientations that can efficiently transfer the bolt to nut or bolt head to shank loads in shear for standard round bolts.

Design of bolted composite lap joints as illustrated in Figure 22 is state-of-the-art technology that has been thoroughly validated. These lap joint designs incorporate 0/90/45/−45 fiber orientations. Typically equal percentages of each are utilized, which is representative of the well-characterized quasi-isotropic lay-up. Although the quasi-isotropic lay-up does not represent the true optimum design, the benefits of the extensive characterization of the quasi-isotropic laminate outweigh other considerations. This state-of-the-art technology was applied to the design of composite fasteners (Miller, 1996).

The "Miller Fastener" illustrated in Figure 23 was developed initially to address a need to attach structural components in augmented gas turbine engine nozzles that are exposed to high temperature exhaust gasses (Miller, 1996). Previous designs of nozzle components required location of highly loaded attachments in areas that are not subjected to the maximum temperature capabilities of the CMC materials since the only structural fasteners available were metal. This restricted the designer's options and resulted in composite designs which were limited by their interlaminar capabilities, i.e., curled liner and rib stiffened liner designs. The fastener design concept illustrated in Figure 23 utilizes the high in-plane fiber dominated strength of the composites to transmit loads. The fastener concept is based on utilizing the basic composite design strategy whereby interlaminar stresses are minimized and the fibers are oriented to transmit the load. The basic fastener is machined from a quasi-isotropic flat laminate as illustrated in Figure 23, thereby assuring the highest quality fastener. The load transfer by shear from the fastener head to the fastener shank is carried by the +45 degree and −45 degree plies. The 0-degree plies along the direction of the shank provide the primary load carrying capability from the liner to the back-structure. The 90-degree plies resist the bending stresses induced in the fastener head. The load is transferred from the fastener to the back-structure using the same composite design philosophy developed for composite lap joints as illustrated in Figure 22, i.e., through a pin in a quasi-isotropic laminate.

As illustrated in Figure 23, the composite fastener can be converted to a threaded fastener without the limitations of previous threaded composite fasteners. This is achieved by utilizing a threaded metal sleeve. The metal sleeve is attached to the composite by a metal pin which transmits the load from the composite fastener to the metal sleeve using state-of-the-art lap joint philosophy which converts shear load into tension and compression in the ±45 degree fibers.

The steps in the assembly illustrated in Figure 23 are: (i) insert the fasteners through the panels, (ii) slide the metal threaded sleeve over the shank of the fastener, (iii) align the holes in the fastener and threaded metal sleeve and insert the pin until it is flush with the base of the threads on the sleeve, and (iv) apply the nut and torque to a predetermined load. The desired amount of preload will depend on the design application and material system.

Figure 24 illustrates the application of the composite fastener in attaching a CMC liner to a metal back-structure. The CMC liners operate at temperatures exceeding the functional operating temperature of metals, but the temperature of the back-structure is below the functional operating temperature of high temperature nickel alloys. The CMC fastener carries the tensile load between the liner and

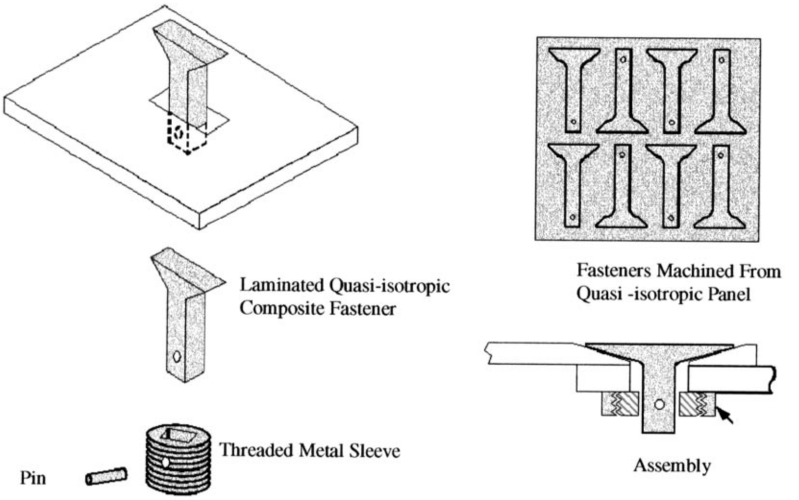

Figure 23 Nonconventional laminated composite fastener.

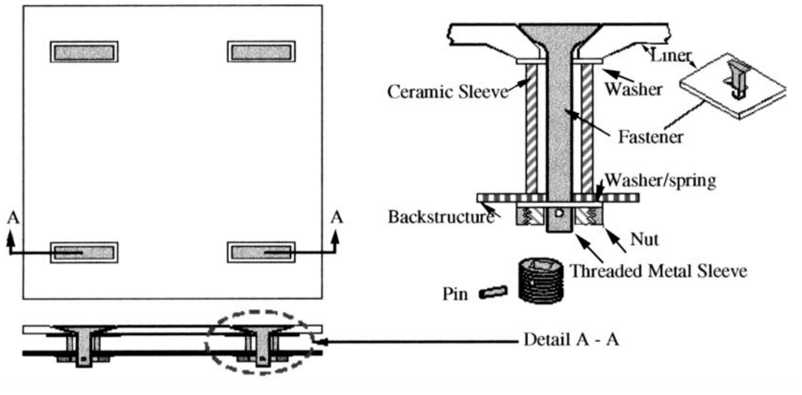

Figure 24 Nozzle liner attachment concept.

back-structure. Since monolithic silicon nitride ceramics exhibit good compressive properties, a monolithic ceramic sleeve is used to carry the compressive load between the liner and the back-structure. Circular or rectangular ceramic sleeves can be used, but rectangular sleeves provide support to the panel when the fasteners are torqued and will prevent panel damage in the event of overtorque. A CMC washer with a rectangular opening can be inserted between the ceramic sleeve and the CMC liner to provide additional support to the liner when a circular ceramic sleeve is used. A spring or Belleville washer is inserted behind the back-structure to provide acoustic damping and thermal relief. After the Belleville washer is applied to the fastener the threaded sleeve is inserted on the fastener shank and the metal pin is inserted in the threaded sleeve and fastener. The nut is then applied and tightened to a specified torque level. As the nut is tightened the load is transferred by pin bearing, as in conventional bolted PMC lap joints, from the metal sleeve to the composite fastener. Traditional threaded composite fasteners rely on shear transfer through threads in the composite resulting in matrix controlled failures. The pin diameter (d), fastener width (w), to hole diameter ratio (w/d), and fastener edge distance (e) to hole diameter ratio (e/d) are determined from standard techniques used for bolted joints in composites and validated experimentally.

The load-carrying capability of the fastener head and the panel can be increased if required by utilizing local buildups as illustrated in Figure 24. The load-carrying capability of the fastener head and panel increase approximately in a linear relationship as the thickness increases. The load-carrying capability of the shank can be increased by increasing the cross-sectional area of the shank. The increase in load-carrying capability of the shank increases approximately in a linear relationship with the increase in the shank cross-sectional area. The use of local build-ups permits the use of fewer fasteners to carry a given structural load, which will generally result in reduced weight as well as maintenance cost.

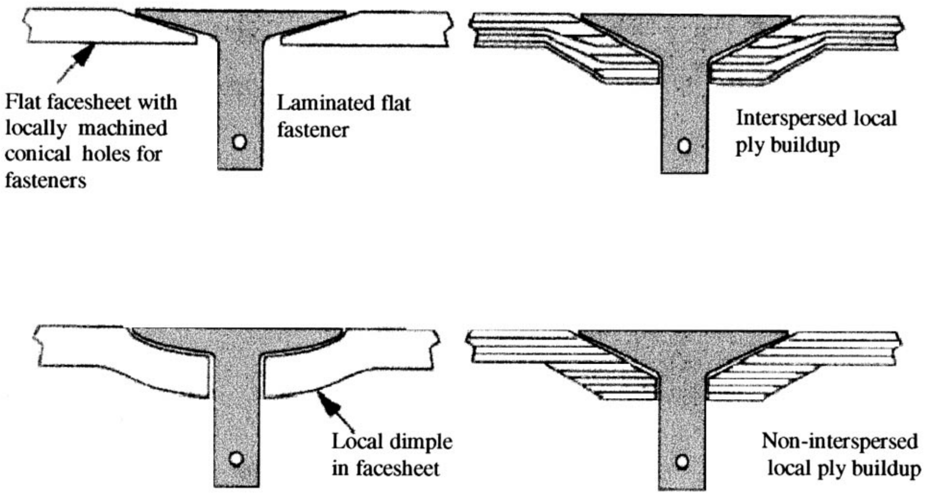

Figure 25 Concepts for panel lay-up.

Concepts for panel lay-up in the region of the fastener attachment are illustrated in Figure 25. The simplest concept is the fabrication of a flat laminated panel with the fastener slot machined in the flat laminate. Another approach is illustrated where the flat panel is dimpled locally during fabrication to accommodate the fastener head and a rectangular hole is machined to accommodate the shank of the fastener. The other approaches illustrate local build-ups in the region of the fasteners. The interspersed is the preferred structural approach although the nondispersed simplifies fabrication. The interspersed approach has been validated in nozzle rig tests.

Three generic attachment concepts using the laminated composite fasteners are illustrated in Figure 26. The first illustrates the application of a threaded metal "T" sleeve which is preassembled to the liner. The assembly steps are: (i) insert the fasteners into the panel, (ii) slide the ceramic sleeve and washer over the shank of the fastener, (iii) thread the nut onto the threaded metal sleeve until it touches the bottom of the "T," (iv) slide the metal threaded "T" sleeve over the shank of the fastener, (v) align the holes in the fastener and metal threaded sleeve and insert the pin until it is flush with the base of the threads on the sleeve, and (vi) torque the nut to a predetermined load. Local channels are attached to the back-structure to provide the groove in the "tongue-in-groove" thermally-free attachment track. The "T tongues" are aligned with the grooves and the liner assembly is slid forward to engage the attachment channels. The edge gap between the "T tongue" and the channel grooves is determined by the thermal growth differential between the liner assembly and the back-structure. The radial gaps generally are determined by the assembly requirements. A design variation permits the use of leaf spring inserts in the channels to keep the assembly tight and provide acoustic damping. Since the liners operate at elevated temperatures, the difference in the thermal bowing of the liners and back-structure will generally maintain a tight fit between the "T" and channels to prevent chattering. In some designs it may be desirable to provide additional radial gap to relieve thermal stresses resulting from out-of-plane thermal bowing. The second approach utilizes the same thermally free attachment but the pre-assembly procedure differs. The fastener is pre-assembled to the liner as described previously but the assembly of the "T" differs. The "T" is pinned (bolted or riveted) to the fastener after the fastener is pre-assembled to the liner. The "T" can consist of a nonthreaded sleeve or a clevis as illustrated. If a clevis is used two pins should be inserted to prevent rotation. In this approach the fastener carries compressive as well as tensile load. The third approach is similar to that shown in Figure 24.

Several attachment concepts for composite nozzle liners utilizing laminated composite fasteners are illustrated in Figure 27. Option (E) illustrates a concept where the liner is supported on a ribbed back-structure. The ribs carry the compressive loads. The fasteners are inserted through the liner and back-structure and the washers, threaded sleeves, and nuts are applied to complete the assembly. Option (D) is similar to option (E) except that the fasteners are pre-assembled to the liner. Option (C) is similar to option (E) except that cylindrical ceramic sleeves are used around the fasteners to carry the compressive load rather than the ribs from the back-structure. Option (B) is similar to option (C) except that the fasteners are pre-

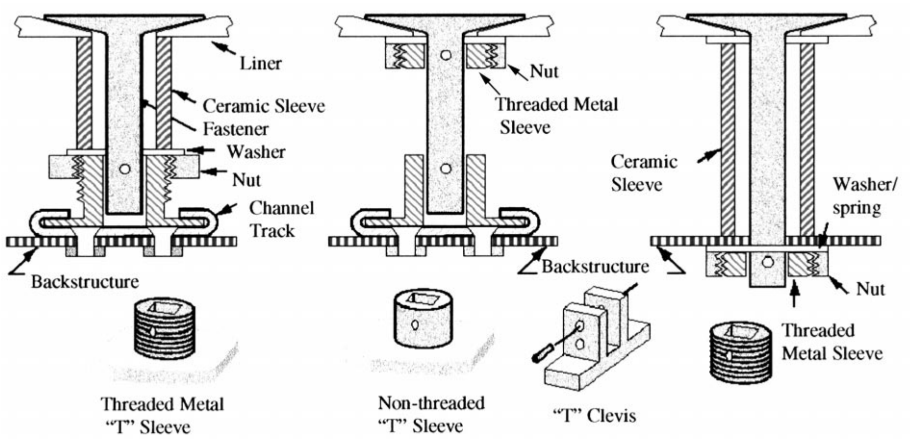

Figure 26 Liner attachment concept using Miller fastener.

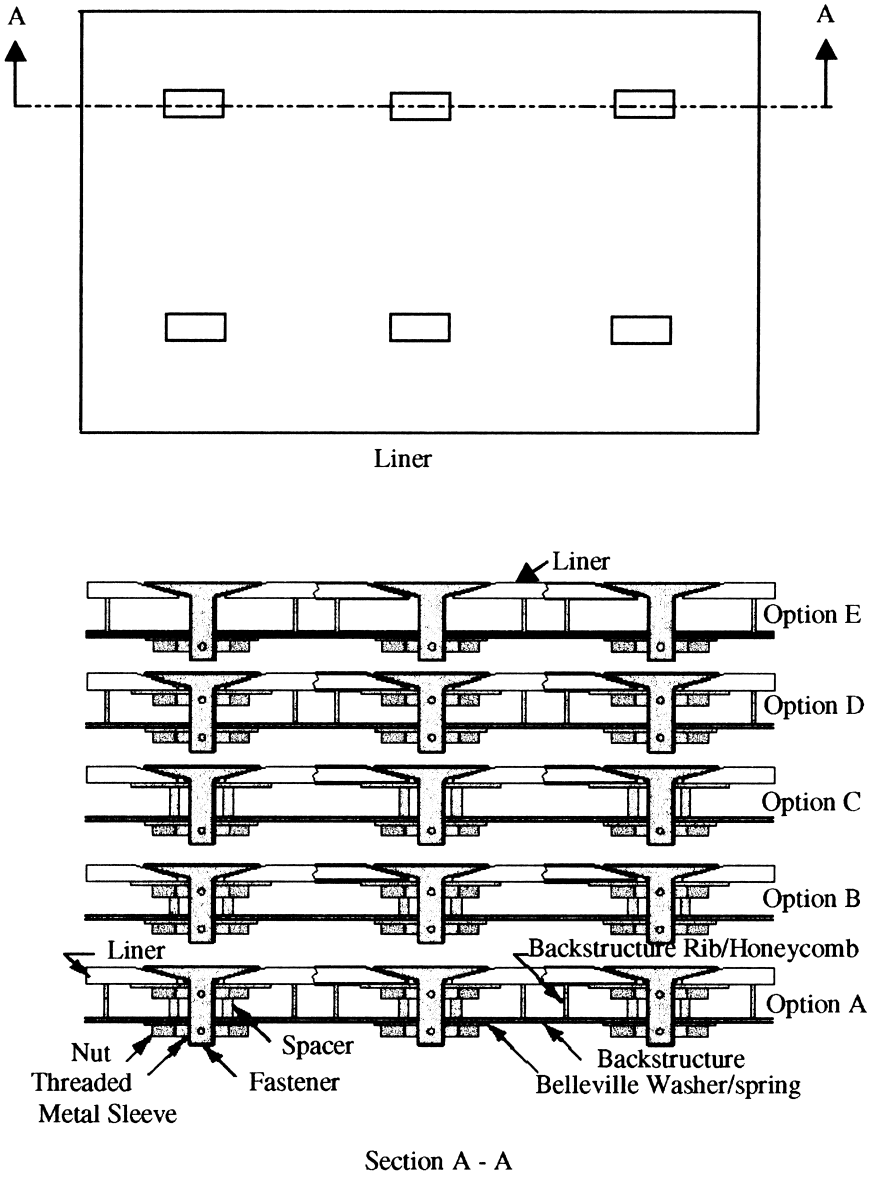

Figure 27 Nozzle liner support concepts.

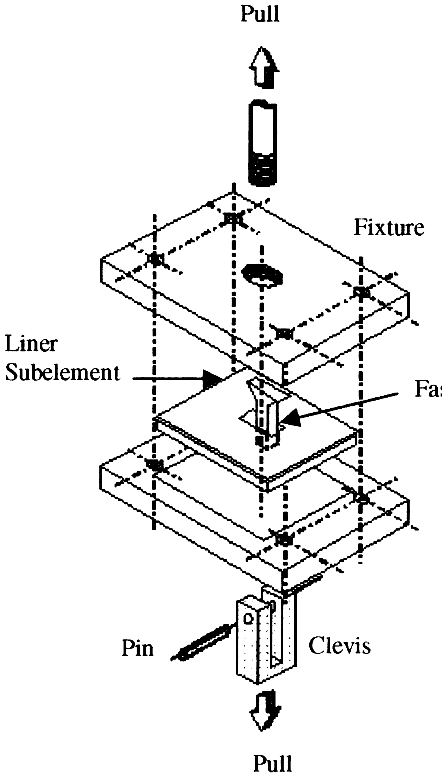

Figure 28 Benchmark test set-up.

assembled to the liner. Option (A) is similar to option (B) except that it also includes rib support between fasteners to provide additional compressive support between fasteners if required. It should also be noted that although the illustration shows all the fastener cutouts in the same direction this might not be optimal to resist multidirectional horizontal shear loads. The design concept permits individual optimization of each cutout angle if required.

This laminated composite "Miller Fastener" described has been validated using extensive subelement and component testing for nozzle liner applications. Figure 28 illustrates the test setup that was used during concept validation testing. The test subelements are a fastener and a 7.5 cm^2 plate with a fastener hole cut in it as illustrated in Figure 28. The panel is simply supported along its outer perimeter by the metal fixture plate. The support plate is attached to an upper metal plate, which is attached to a tensile test machine. The fastener is connected to the test machine using a clevis and metal pin representative of that used to attach the threaded metal sleeve in actual practice. The test rig was used to perform static, creep, and cyclic loads. Tests can be conducted at room or elevated temperatures including the environmental testing described in Section 6.10.5.

The attachment concept relies only on the ability to fabricate flat quasi-isotropic laminates. Flat laminates offer the ability to fabricate the highest quality and lowest cost components using any fabrication methods, including hot pressing and compression molding. Also, the flat laminate fastener design permits utilization of the highest reliability NDE methods developed for the inspection of material characterization panels. The fasteners utilize a threaded metal sleeve to permit utilization in a similar manner as a typical bolted metal fastener. Previous composite bolts relied on threads in the composite that result in low load-carrying capability due to interlaminar failure in the threads.

The "Miller Fasteners" are not restricted to high-temperature CMC applications. The design has significant benefits when attaching low observable materials, including polymer matrix composites. The fasteners for attachment of PMC structures could be fabricated from the same material as the structural component, which would maintain a desirable match of dielectric constants.

6.10.7 REFERENCES

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Comprehensive Composite Materials
ISBN (set): 0-08 0429939

Volume 6; (ISBN: 0-080437249); pp. 181–207