Durable and Damage-Tolerant Composite Commercial Aircraft Structure Design Approach

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The technical information needed to competently assure the safety and durability of composite commercial aircraft structure must include a broad base of disciplined test-validated analytical procedures supported by an extensive material and structural test data base. This paper briefly addresses the safety and durability goals and requirements. A plan for development of an analytical methodology and the required data base and a cursory assessment of the success potential for this plan are presented. Some test results related to the required data base are also presented.

Introduction

FOR advanced composites to be applied successfully to commercial aircraft primary structure it must be demonstrated that its applications will improve the profitability of the airlines and the airframe manufacturer. In addition, all composite applications must maintain or improve the level of safety currently provided by metallic structure.

Designs using composites in primary structures still require considerable development and verification before they are accepted and can be committed to use in commercial aircraft. The current trend in product liability requires that considerable care be used to establish the same degree of safety and durability that is currently available. Commercial aircraft are designed for a productive life of 20 years. Typically, in commercial aircraft produced today some form of warranty and service life policy is required from the manufacturer, and we must provide one. Also, from the airlines point of view, their current tight economic situation will not allow them to incur an economic disappointment because of a commitment to an aircraft containing a new material system. Therefore, we must do our homework thoroughly in every aspect. The new material system must not contain any maintenance or durability fatal flaws, and its cost effectiveness must consider both the initial cost and the cost of maintenance. These foregoing statements are obvious and redundant in view of many papers that have been presented on this subject. However, the impact of safety and economics on the acceptability of advanced composites in primary commercial aircraft structure remains unchanged.

This paper will address the subject of damage tolerance and durability which are directly related to safety and economics as shown in Fig. 1. The objectives of the damage tolerance (fail-safe) philosophy in the commercial aircraft connotation is simply stated as: the structure must be designed in such a way that any damage incurred from normal operation is detectable before the strength or stiffness of the structure falls to an unacceptable level. The anticipated damage that may arise from normal aircraft operation can include fatigue damage, manufacturing and/or maintenance flaws or errors, and undetected accidental damage. The damage tolerance designed structure must also provide a very substantial measure of protection against accidental damage sustained in flight as a result of such things as engine breakup, hail, bird, or other types of impact damage. In these particular cases it is expected that the damage will be found upon completion of the flight. Intrinsic damage such as fatigue damage caused by environmental and load exposure from the time the aircraft is delivered must be detected during routine maintenance and inspection before the residual strength reaches an unacceptable level.

The service life of a damage tolerant (fail-safe) designed aircraft structure is determined more by its operational efficiency and technology state-of-art. There is no structural limit to the aircraft's service life since all damage to structural components in a damage tolerant (fail-safe) structure can be detected, repaired, or replaced. The cost and frequency of repair or replacement significantly impacts the aircraft's operational cost effectiveness and therefore the durability of the damage tolerant structure may limit the economic life of the aircraft.

This paper presents a cursory look at an approach to the analytical and data requirements to support the commercial design philosophy and certification requirements for composite structure. The primary objective of the suggested plan is to develop the data base and analytical processes as the prime means of certification of composite commercial aircraft structure. For the durability (fatigue) assessment of composites an approach is suggested that steps off from a currently applied metal procedural base. The data and design information that are currently being generated by both composite technology and component development programs will support this approach. Similarly, the information for damage growth under repeated loads and residual strength

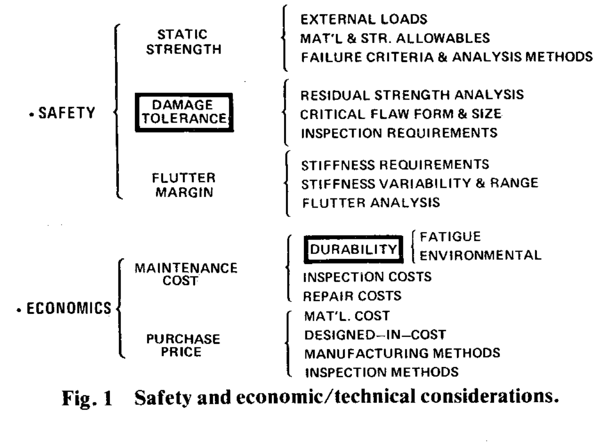

Fig. 1 Safety and economic/technical considerations.

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data are being generated that will support the analytical requirements. Some IR&D generated data which examines several parameters associated with durability, fracture, and residual strength are shown.

Requirements

Before addressing the specific requirements that must be met by this approach we need to establish a philosophy concerning the overall design requirements. The philosophy we have taken concerning the design requirements is based on the belief that there is no need to deviate from the commercial design philosophy which has proven very successful for our present form of design and construction. This current philosophy has evolved over a long period of time and has been validated by the long-term service experience of many aircraft. This basic design approach is based on a design for safety which has as its central philosophy the fail-safe design approach. In changing over to composite structures, we must follow these same design fundamentals. However, the details of the methodology must inherently be different for a different material system. The principal problem in developing these detail methodologies for composites will be to accurately describe and predict the multiple failure modes that are characteristic of composite laminates.

The specifics of the design to meet the safety standards are guided by the FAA certification regulations. In complying with the present regulations the airframe manufacturers and the FAA have achieved an outstanding safety record for our commercial aircraft fleet. Because of this record and the continuing commitment to the fail-safe (damage tolerance) philosophy, we believe that the current regulations are adequate for certification of composite structure. In complying with the regulations to certify composite structure, the unique features of composite structure will have to be adequately assessed. For example, one such item that must be covered is the effects of temperature and moisture on composite material properties and structural element damage tolerance. This accountability must be demonstrated through test at several levels of structural details. In addition, its accountability must be covered by analysis which reliably correlates test data, since all structural elements cannot be tested. This last requirement is the key to attaining the aforementioned goal of having analytical tools available as the primary means of certifying the composite structure.

Compliance items of the current regulations that are of prime concern for composites are material properties (25.603a and 25.613,[‡] static strength validation (25.305 and 25.307), and durability (fatigue) and damage tolerance (fail-safe) (25.571). For the materials area, the methods and depths of testing and analysis required to validate material allowables at both lamina and laminate levels, while adequately accounting for effects of temperature and moisture will be essential. This temperature and moisture accountability is also necessary for the full-scale validation of the structure's static strength and damage tolerance. The ability to scale up the moisture and temperature effect is crucial to the success of the application and certification of composite structure. For the damage tolerance (fail-safe) compliance to be successful, it is absolutely necessary that damage detection procedures for in-service inspection be available. Finally, another very important item of compliance will be the adequate control of the material through material and process specifications (25.603b and 25.605) that can provide repeatable material characteristics so that the accountability of the key structural failure modes can be consistently predicted by analysis.

Design and Analysis Approach

The approach to the development of the data and analytical procedure suggested by this paper was selected on the basis of the best means to achieve the following goals:

The overall goal of the procedure must be to establish analytical processes as the prime tool for structural validation and certification of composite structure.

The quality of the analytical procedure must be such that any required full-scale testing would only be used to provide for aircraft growth or to uncover human error in the application of the analysis or manufacturing procedures.

The procedure must be capable of being implemented in a simple and economic manner similar to the most common approaches used in the strength analysis and design of today's aircraft.

The procedure must be useable within the constraints of today's limited data and flexible enough to improve with the continuing expanding data base.

The procedure must be able to provide acceptable and certifiable validation of the safety and durability of all primary structural elements.

The procedure must be capable of impacting the design as well as being used to analyze the design.

The procedure must be capable of being validated by test.

The procedure must be highly disciplined so as to be useable by a large design team.

The procedure must be definitive in its evaluation of the design variables so that a safe and cost effective design can be developed from the design alternates.

The first step in establishing the type of approach to be used was to assess the data needs, the data availability, the data to be made available, and the time period in which these data would be available. Also, the potential for developing adequate analysis coverage within various time periods must be considered. We have separated the time periods of data development and composite applications into three sections as shown in Table 1.

First, simple test data will be produced in the near term (Period 1, Table 1) to understand the various failure modes, and basic material properties will be generated to support specific or single-point design. These data will probably be based on ultimate load requirements, spectrum requirements, and damage-tolerant requirements of the specific component. In the second time period (Period 2, Table 1) more complex structures will be tested and evaluated and specific types of failures will be investigated in more detail. And, finally, in the third period, (Period 3, Table 1) major pieces of complex structure will be designed which must be supported by analytical procedures. In this time period both full-scale and detail tests will be available. The validation of the analytical methods will be accomplished by utilizing the parametric and point design data generated in Periods 1 and 2 together with the test results from Period 3.

The flow of data and procedure development is dependent on and will parallel the anticipated component developments currently occurring in the commercial airframe industry under the NASA sponsored Aircraft Energy Efficiency (ACEE)

Table 1 Composite structure analysis and testing data time flow

	COMPOSITE STRUCTURE ANALYSIS AND TESTING	PERIOD 1 3 TO 6 YRS.			PERIOD 2 6 TO 9 YRS.			PERIOD 3 9 TO 12 YRS.		
		STATIC	FATIGUE	DAMAGE TOLERANCE	STATIC	FATIGUE	DAMAGE TOLERANCE	STATIC	FATIGUE	DAMAGE TOLERANCE
ANALYSIS	LAMINATE STRUCTURAL ALLOWABLES	■			■			■		
	STRUCTURAL DETAILS									
	– STRENGTH	○			○			■		
	– STABILITY	○			○			■		
	– STIFFNESS	○			○			■		
	COMPONENTS									
	– SERVICE LIFE		○			○			▲	
	– FRACTURE			○			○			▲
	– FLAW GROWTH		○			○			▲	
TESTING	MATERIAL ALLOWABLES	■			■	○				
	GENERIC DETAILS					○		■	○	
	DESIGN DETAILS	■	○	■	■	○	○		○	■
	SUBCOMPONENTS	■	○	■		○	○			
	COMPONENTS		○	■						
	FULL SCALE MAJOR ASSEMBLIES	■ ULT	○	■	■ ULT	○	■	■ LIMIT	○	■

■ CERTIFICATION REQUIREMENT
○ DESIGN REQUIREMENT
▲ ANALYTICAL DEVELOPMENT AND VALIDATION

‡Numbers refer to Federal Aviation Regulations, Part 25.

Table 2 Common approach to static, fatigue, damage growth, and residual strength design

ANALYSIS	ULTIMATE STRENGTH	FATIGUE STRENGTH	DAMAGE GROWTH	RESIDUAL STRENGTH
REQUIREMENT	ULTIMATE DESIGN STRESS	FATIGUE DESIGN QUALITY	GROWTH RATE REQUIRED	RESIDUAL STRENGTH STRESS
	f_{tu}	$FQ_{REQUIRED}$	$\left(\frac{dA}{dN}\right)_{REQUIRED}$	f_{RS}
CAPABILITY	MATERIAL ALLOWABLE	DESIGN QUALITY	GROWTH RATE DETAIL	MATERIAL RESIDUAL STRENGTH
	f_{tu}	FQ_{DETAIL}	$\left(\frac{dA}{dN}\right)_{DETAIL}$	F_{RS}
MARGIN	$\frac{F_{tu}}{f_{tu}} -1$	$\frac{FQ_{DETAIL}}{FQ_{REQUIRED}} -1$	$\frac{\left(\frac{dA}{dN}\right)_{DETAIL}}{\left(\frac{dA}{dN}\right)_{REQUIRED}} -1$	$\frac{F_{RS}}{f_{RS}} -1$

programs. If one follows the flow of data and analysis development illustrated in Table 1, it can be seen that it is directed to again meet the long-term goal of establishing analytical procedures as the prime tool for structural validation and certification of composite structures.

Since most technology developments step off from the current technology base, this is the approach applied to the plan outlined for development of the composite analysis methodology. By examining Table 2 we see that the generalized steps for analytical validation of each of these structural modes can be defined by a similar disciplined procedure. A discussion of some of the aspects of structural durability and damage-tolerant design for composite structure is presented in the following sections together with some recently generated test data.

Structural Durability

Figure 2 illustrates a step-by-step procedure used to obtain an assessment of the fatigue quality of a structural element. The procedure is divided into two aspects: 1) establishment of the required durability and 2) the detail quality or capability of the final detail. Those aspects of the analysis for which there is no change from the current metals technology and those that are affected due to the nature of advanced composite material are noted in Fig. 2. The life goals, aircraft usage, and the general aspects of required reliability are unaffected by the use of composite materials. The stress environment is affected in that it must be selected to reflect the appropriate controlling composite stresses as defined by the methodology. Damage analysis is the model required to assess the service usage effect of repeated loading on the composite material. On the capability side are the two configuration effects. The gross configuration refers to the general structural layout and material selection. The detail configuration refers to specific structural details such as local reinforcing for mechanical fastening, cutouts, and stiffener runouts. By comparing the quality of the detail with the quality required, the durability of the part being analyzed can be quantitatively established. Those areas that are identified as being affected by the application of composites, as shown in Fig. 2, are directly associated with the developmental areas that must be addressed for advanced composite structure.

Figure 3 defines the obvious developmental tasks that need to be addressed. Each of these areas have been addressed by many different composite technology investigators. However, from a review of literature, there appears to be no integration of all aspects into a single application procedure.

Failure of composite structures due to repeated loading (fatigue) must be defined by applying intuitive reasoning, engineering judgment, analytical information, and test data. The fatigue performance of composite structure for commercial aircraft application must be defined by a characteristic detectable damage and this detectable damage must occur significantly prior to a reduction in strength below the defined safe limits. This requirement is illustrated in Fig. 4. The fatigue performance of composite elements will be extremely difficult to estimate because of the multiple failures possible, namely, fiber and/or matrix, and the dependence of these failure modes on the loading environment.

Loading environment, effects of stress ratio, and stress level are important and necessary parts of the durability technology. An understanding of loading environment effects on composite structure will be more complex than that for metal structures because composite structures are more sensitive to stress ratios. This phenomena was demonstrated in a recently conducted company sponsored test program on fatigue of graphite mechanical joints. Figure 5 shows typical failed specimens and Fig. 6 shows the fatigue test results for stress ratios $R = -0.3$, -1.0, 10.0, and 0.10.

A definitive damage rule must be developed for composite structure which will provide a correlation between constant amplitude cyclic and spectrum testing. This correlation is essential for design, since it will be neither technically nor economically feasible to evaluate all composite details by spectrum testing.

Those areas that routinely contain different characteristic fatigue loadings for commercial aircraft are illustrated in Fig.

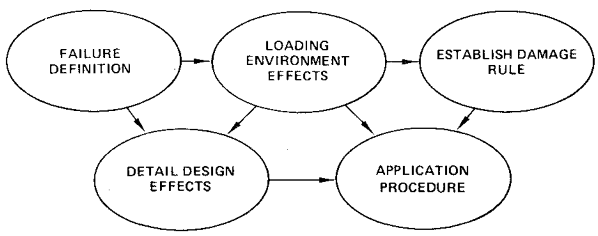

Fig. 3 Development areas of fatigue technology.

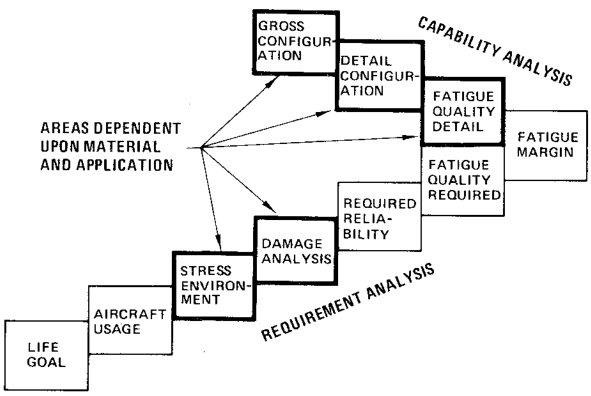

Fig. 2 Example of a fatigue check procedure.

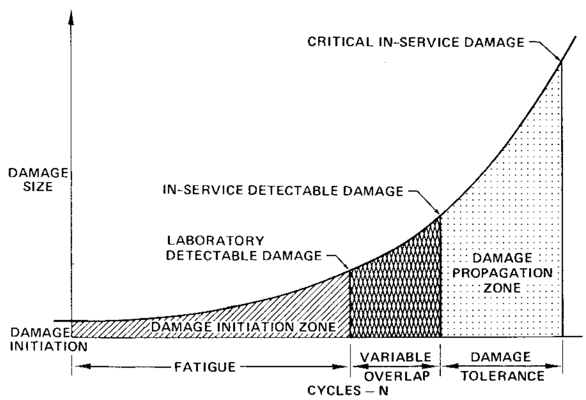

Fig. 4 Durability/damage-tolerance considerations.

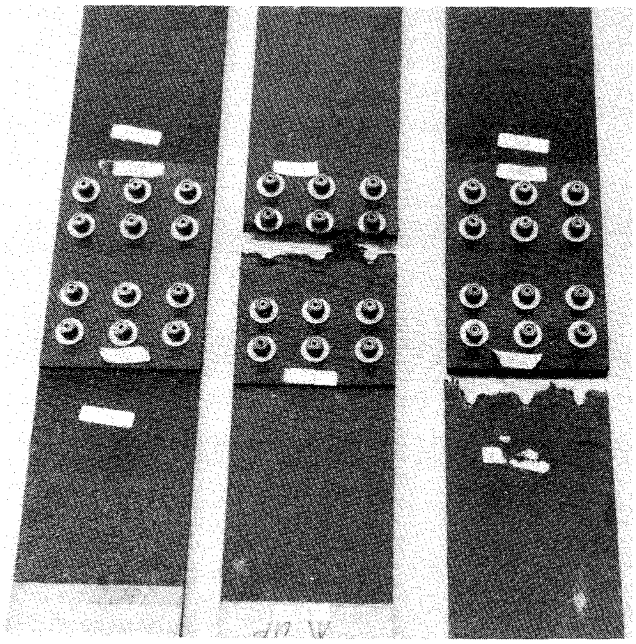

Fig. 5 Graphite mechanically fastened joint specimens.

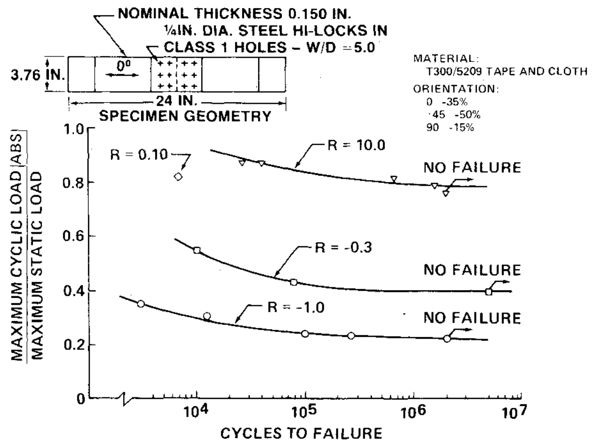

Fig. 6 Fatigue performance of a graphite mechanically fastened joint at stress ratios $R = -0.3$, -1.0, 10.0, and 0.10.

7. Figure 8 illustrates typical fatigue damage effects and variation in tension stresses for a wing lower surface. These illustrations point out the large number of areas that must be analyzed and serve to emphasize the need for a constant amplitude cyclic to spectrum repeated load correlation. In addition, this damage rule should be capable of being applied in a simplified format similar to Miner's damage accumulation rule.

Detail design effects on the durability of composite structures will be an equally important technological area as it is for metal structures. Fleet service history of today's commercial aircraft indicates that design details cause the highest percentage of fatigue problems. Figure 9 presents data obtained from two programs recently conducted at Boeing. The results point out the different fatigue performance that resulted from the two design details. The same laminate orientation was used, and the same stress, as a percent of static tension ultimate, was used for both programs; however, the thickness, material, and test specimen geometry were different. The major objective of the durability technology program should be to provide the analytical model to predict the differences as illustrated in Fig. 9.

The application procedure, as previously shown in Fig. 2, requires the development and understanding of fatigue

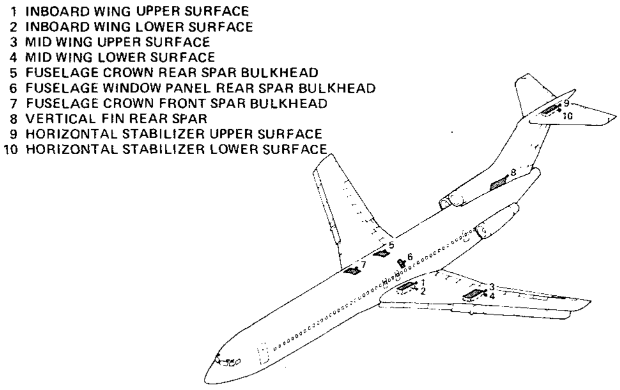

Fig. 7 Examples of typical fatigue analysis locations.

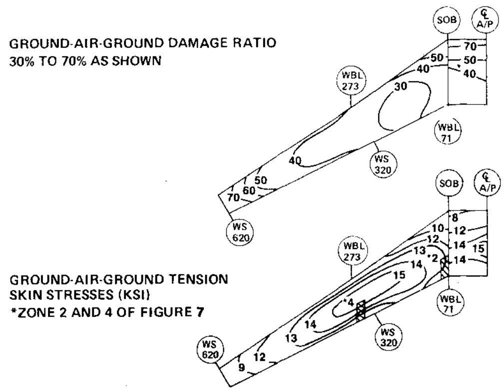

Fig. 8 Typical fatigue damage effects and tension stresses for a commercial transport wing lower surface.

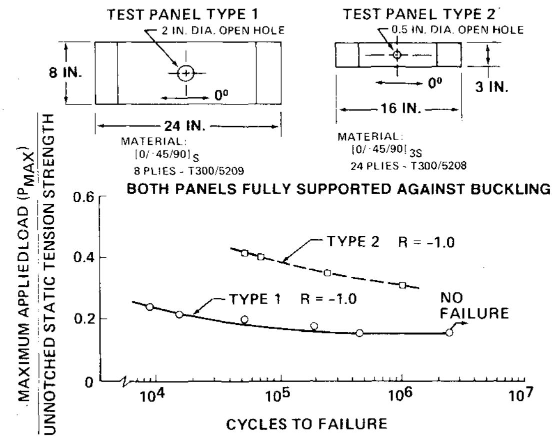

Fig. 9 Fatigue test results for two panel geometries at a stress ratio $R = -1.0$.

failure, loading environment effects, damage rule, and detail design effects. When all of these technologies are developed and assembled into a related procedure, then durability analysis can be treated in an analogous manner to that presently done for strength analysis as previously outlined in Table 2.

Damage-Tolerant Design

The emphasis placed on damage-tolerant (fail-safe) design in commercial aircraft is a realistic recognition of service experience. All current aircraft structure experiences intrinsic flaw growth or sustains externally imposed damage. There is no rationale that says this will change for composite structures. Critical design areas previously noted in Fig. 7 will most likely be potential locations for flaw initiation and growth. If

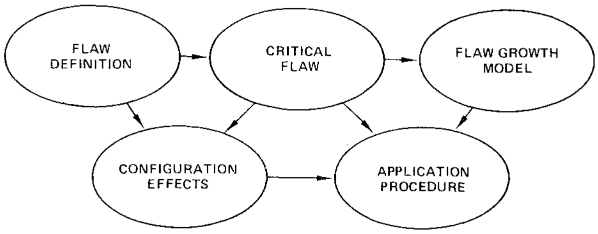

Fig. 10 Development areas of damage-tolerant technology.

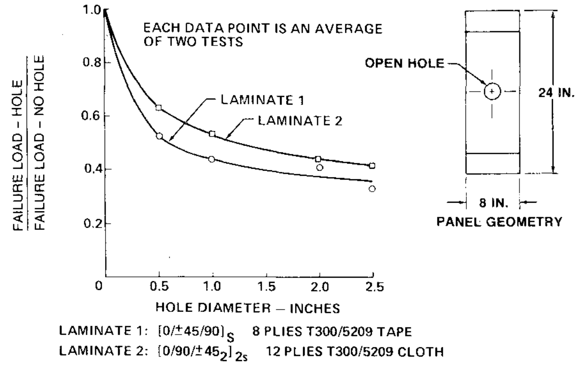

Fig. 11 Tension strength of graphite laminates with open holes.

flaw growth and damage are accepted as occurring in composite structure, then the design of damage-tolerant structure requires the ability to detect this damage before it becomes critical. This detection capability must be defined by service inspection capabilities. Inspection is the only technology required outside the basic scope of structural mechanics. The establishment of detection levels dictated by the design vs the detection capability requires that the inspection and structural mechanics disciplines work closely together.

Inspection capabilities must define the largest non-detectable damage, and the structure analyst must define the largest acceptable damage. Damage form must also be defined for composites. The current ability of either discipline to define their needs is questionable. Much work is still required to meet the inspection capability and define the degree of allowable damage for commercial aircraft.

The structural mechanics damage-tolerance technology areas that must be developed are shown in Fig. 10. This figure parallels that previously presented for durability (Fig. 3). Also, the analytical precedural steps previously defined in Table 2 apply equally well to damage growth analysis. Flaw or damage definition, for intrinsic flaws, is identified as fatigue failure as noted in Fig. 4. Externally imposed damage must be defined by the potential service environment as previously noted, and all damage that is initially critical must be safely contained until the completion of the flight. It is further assumed that this damage is obvious at completion of the flight.

The damage that develops following external initiation must grow in a time span that allows detection before it becomes critical. These growth and detectability requirements are essentially the same as for intrinsic flaw growth and in all likelihood the growth forms will be similar for both cases. Since externally imposed damage, which is initially critical, requires only the development associated with establishing critical damage level, the following discussion will cover only the intrinsic flaw case.

As previously noted, flaw definition may be established, in at least appropriate categories, by the definition of fatigue failure. The primary technology that needs to be developed is the ability to project the damage growth rate with the required accuracy. It should be emphasized that the accuracy with which one predicts the time interval from initial flaw growth

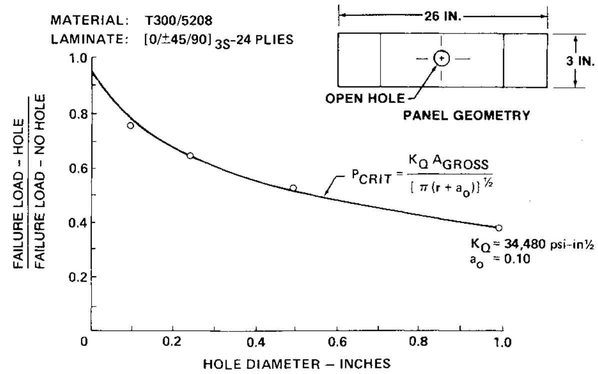

Fig. 12 Residual tension strength test data for a T300/5208 graphite laminate.

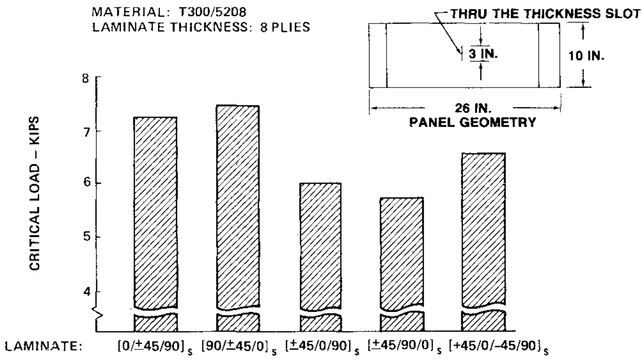

Fig. 13 Influence of stacking sequence on fracture strength of a center-notched graphite panel.

to detectable size (fatigue failure) is of economic consequences, whereas, the accuracy of predicting the growth rate of the detectable flaw to critical size is concerned with safety as previously shown in Fig. 4.

The critical flaw size for any composite structure is influenced by the following: type of material, thickness, laminate orientation, and stacking sequence; type of flaw; and ratio of fiber strength to interlaminar shear strength.

Some of these influences have been demonstrated by tests recently conducted at Boeing. Figure 11 illustrates the influence of material type and laminate thickness and orientation. This figure compares the results of various hole sizes in T300/5209 tape and cloth laminates. Figure 12 contains the test results of holes in T300/5208 laminates. These data were analyzed using the method proposed by Waddoups et al.[1] This analysis provided reasonable agreement as shown, and the characteristic values of stress intensity factor (K_Q) and intense energy region (a_0) are as indicated.

The work recently performed by Porter[2] illustrates the influence of flaw type on residual strength. This test program evaluated the effect of full- and half-penetration circular holes. These results also showed reasonable correlation with the method proposed by Waddoups for tension loaded structure.

The influence of stacking sequence on residual strength of an eight-ply laminate is shown in Fig. 13. Figure 14 is a photograph of two of the failed panels showing the different failure modes. The $[0/\pm 45/90]_s$ laminate failed by a clean break with minimal fiber pullout at a critical load of 7240 lb. The $[\pm 45/90/0]_s$ laminate failed with significant fiber pullout at a critical load of 5740 lb.

The influence of the ratio of fiber strength to interlaminar shear strength on critical flaw size has been recognized by Cooper.[3] In this presentation, he defined four mechanisms that contribute to fracture toughness. These four mechanisms are quoted as follows: plastic deformation of the matrix,

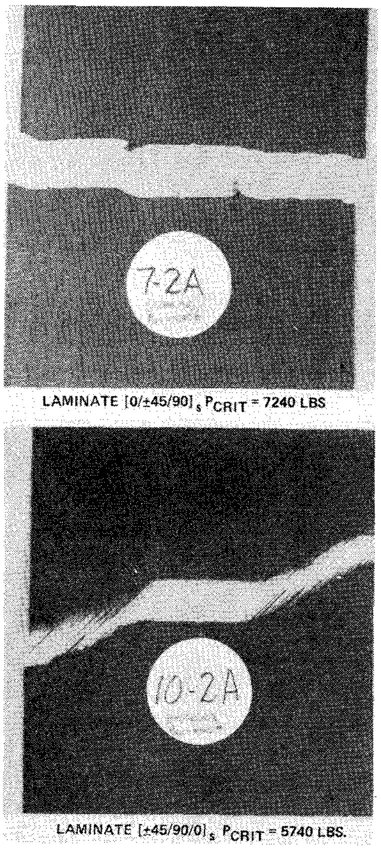

Fig. 14 Comparison of failure zones in fracture panels.

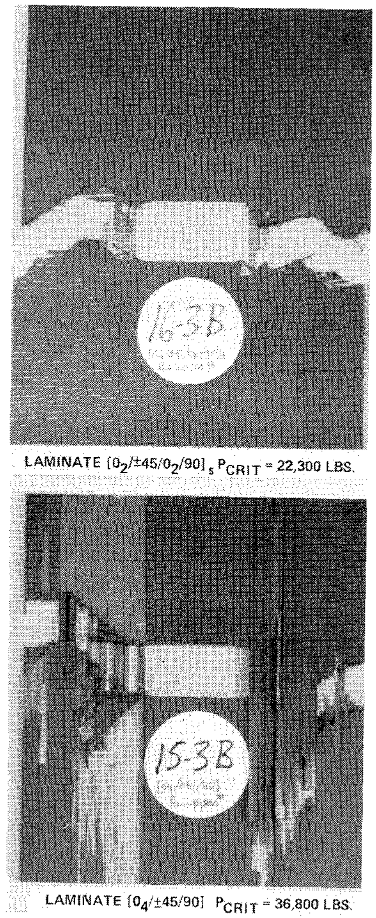

Fig. 15 Photograph of failed fracture panels.

plastic deformation of the fibers, work done in debonding the fibers from the matrix, and work done in pulling the fibers out of the matrix. The influence of debonding and pulling fibers from the matrix is dramatically illustrated in Fig. 15. The laminate defined as $[0_2/\pm45/0_2/90]_s$ failed at 22,300 lb and the laminate defined as $[0_4/\pm45/90]_s$ failed at 36,800 lb. The significant amount of fiber pullout and energy absorbed by delamination in the panel with the lumped 0-deg fibers is illustrated in the figure.

A flaw growth model must be developed to provide the ability to accurately predict the service interval between the time the damage is defined as detectable and the time the damage grows to critical size. This growth prediction capability is absolutely necessary in the design of damage-tolerant structure.

At the present time, very minimal experimental work is being performed in this area. The work of Kunz and Beaumont[4] demonstrated that linear elastic fracture mechanics can be applied to damage growth in 0/90 graphite laminates. This test program was successful since the damage propagated by fiber failure and could be readily measured by optical means. The analysis by McLaughlin et al.[5] is presented as being capable of predicting fatigue crack growth. However, as the authors state, no test data are currently available to verify the analysis. The general case of damage propagation in more complex laminates is seriously hampered by the lack of definite inspection techniques.

The paper presented by Marcus and Stinchcomb[6] points out that radiographic and thermographic methods can be used to monitor damage growth in boron laminates. The inspection methods of holographic interferometry, ultrasonics, penetrant, and x-ray radiography employed by Salkind[7] produced results of varying quality. However, as Salkind points out, and the present authors agree, even though these methods are technically and economically feasible for damage detection, their effectiveness depends on developing a quantitative data base relating damage to residual strength.

Configuration effects significantly alter the damage-tolerant capabilities of composite structures. Researchers have evaluated the damage tolerant capabilities of soft skins and stiff straps[8] and the reverse condition of stiff skins and soft straps.[9,10] Both designs proved to be acceptable based upon the design loads and criteria.

Discussion up to this point has primarily been concerned with tension-loaded structure. The damage-tolerant capability of compression-loaded structure has received minimal attention by most researchers. A test program being conducted at NASA Langley Research Center[11] indicates that impact-damaged graphite composite laminates are extremely sensitive to compression loading. The rate of damage growth for panels subjected to compression dominated repeated loading has not been investigated and, as a result, the magnitude of this effect is not known.

The application procedure for designing damage-tolerant composite structure requires the development of the technologies as previously shown in Fig. 10. Research is being conducted in many of these areas as noted in the referenced technical studies. This research must continue to develop a disciplined test validated analytical procedure.

Conclusions

This paper has presented a review of some of the information needed and a limited suggestion of a plan to develop the analytical methodology and required data base to confidently assure the safety and durability of advanced composite structure. A methodology that parallels that presently used for the durability analysis of metal structures has been proposed for composite structures. The necessity for a damage-tolerant structure has been presented, and the need for development of this discipline has been discussed. The ability of the proposed plan to use the information generated by composite development programs to build the required data base for analysis validation has been stressed. The areas that are considered critical to the development of a disciplined analytical procedure for durable and damage tolerant structure are summarized as follows:

Establish the fatigue quality of design details that are commonly found in commercial aircraft structure. This quality rating must include the effects of material type and thickness, stress level, and configuration effects such as degree and mode of load transfer.

Establish a damage rule that provides a correlation between constant amplitude and spectrum loading.

Develop inspection methods for damage detection in composite structures that are technically and economically feasible for in-service use.

Develop a qualitative data base that relates the degree of damage to residual strength.

In an attempt to project the potential of the proposed plan for the successful development of durable and damage-tolerant structure, the strengths and weaknesses of this approach are presented as follows:

The primary strength of this approach is that it is based on a simple disciplined analytical methodology that can be validated by test. In addition it is strengthened by the proven success with metal structures in commercial aircraft.

The primary current weakness of this approach is the present lack of experimental and service data for correlating the analytical procedures. In addition the impact on the disciplined procedure of the increased number of material and structural variables has yet to be assessed thoroughly.

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