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COMPOSITE FUSELAGE TECHNOLOGY

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PREFACE

This work was conducted at the Technology Laboratory for Advanced Composites (TELAC) in the Department of Aeronautics and Astronautics of the Massachusetts Institute of Technology with Professor Paul A. Lagace as the Principal Investigator. The work was funded by the NASA Langley Research Center via NASA Grant No. NAG-1-991. The work was performed during the period from April 7, 1989 through July 31, 1999.

INTRODUCTION

The aircraft industry continues to pursue the use of advanced composite materials in aircraft structures in order to save weight and produce more efficient, and potentially cost-effective, aircraft. As of the beginning of this work in 1989, advanced composite materials had been applied for over two decades in a number of aerospace structures. Although the list of applications at that time (including aircraft such as the Boeing 757 and 767, the Beech Starship, The Osprey V-22, the F-18, and the AV-8B) represented important engineering achievements, the National Research Council Committee on the Status and Viability of Composite Materials for Aircraft Structures noted in its 1987 report that: "Despite these and other examples, filamentary composites still have significant unfulfilled potential for increasing aircraft productivity [1]."

An area identified for application of composite materials, at the time of this work, was primary load-bearing structure in large commercial transports. Although smaller aircraft, such as the Beech Starship, have had primary load-bearing structure, such as wings and fuselages, constructed from composite materials, it is not practical to geometrically scale up a general aviation aircraft into a large transport due to differences such as in the loading indices.

There was thus an identified need to pursue further research into the behavior of composite materials and their structures so that increased benefits, such as further reduction in the structural load fraction, can be achieved. Two critical technology areas as related to aircraft are the technologies associated with wings and with fuselages. In considering such applications, an overriding concern is safety. In and of itself, safety is a very wide ranging issues. But, with regard to structure, safety generally deals with the ability of the structure to maintain its integrity while subjected to the loads and environment experienced in operation.

A central issue in the case of a primary load-bearing structure is damage. There are three facets to the central issue of damage: *damage resistance*, which involves the ability of a structure to undergo events without (minimal) damage occurring and which thus addresses the question "how does damage get there"; *damage tolerance*, which involves the ability of a structure to undergo loading with damage present without failing and which thus addresses the question of "when does damage propagate/cause failure?"; and *damage arrest*, which involves the ability of a structural configuration to stop propagating damage before such damage causes catastrophic failure and which thus addresses the question "how can the propagating damage be stopped?". Answers to these three questions must be provided in order for a safe structure to be designed.

In addressing these issues as they pertain to fuselage configurations made from advanced composite materials, a number of other important technical issues arise. A key issue is that of orthotropy. Due to their inherent orthotropy, composite materials provide the designer the ability to vary the properties of the structure with the structural needs in the various directions of the structure. This "structural tailoring" will affect the damage issues previously enumerated and the designer needs to know how to best tailor the specific fuselage structure to meet the structural needs and to meet the demands placed by the damage issues of resistance, tolerance, and arrest.

A further issue deals with the effects of size. Aircraft fuselages are constructed of various dimensions and test articles are often of much smaller size. In order to apply the technology across the entire spectrum of possible sizes, it is necessary to understand the role of scale in the three damage issues. If scaling "laws" or working principles can be established, then the data and lessons learned on one fuselage can be more readily transferred to that of a different geometry and size.

A final issue that could be immediately identified was that of configuration and its effects on the three facets of damage. A common structural configuration for aircraft fuselages is that of skin and frame where the underlying frame carries the longitudinal and bending loads while the skin provides the pressure surface and shear capability. In contrast to this typical approach used in metallic airframes, the Beech Starship fuselage has a more monocoque configuration utilizing a sandwich structure with inner and outer graphite/epoxy skins surrounding a Nomex honeycomb core. In this configuration, the sandwich skins provide the bending, longitudinal, pressure, and shear capabilities of the fuselage. In the skin/frame configuration, issues such as the interaction between the skin and the frame and how the skin is attached to the frame must be treated. In the sandwich configuration, issues concerning sandwich construction including debonding of the skins from the honeycomb must be addressed. Again, these need to be addressed in the context of the three facets of damage as to how they affect damage resistance, damage tolerance, and damage arrest. The underlying need is to provide the structural designer with the capability to choose the structural configuration that will most efficiently carry out its mission.

OBJECTIVES

The overall objective of this work has been to identify and understand, via directed experimentation and analysis, the mechanisms that control the structural behavior of fuselages in their response to damage (resistance, tolerance, and arrest). A further objective has been to develop straightforward design methodologies that can be employed by structural designers in preliminary design stages to make intelligent choices concerning the material, layup, and structural configuration so that a more efficient structure with structural integrity can be designed and built.

(INITIAL) GENERAL APPROACH

Although there are three different facets of the damage issue and these facets do interact, it is possible to first pursue these independently: damage resistance, damage tolerance, and damage arrest. This multiple year effort began with careful consideration of work available in the open literature on damage in general composite structures (e.g. Reference 2) and damage specifically in fuselage type structures made of composites (e.g. Reference 3).

The initial work focused on damage growth and arrest. It has been shown [4] that the direction of damage propagation can be changed by the particular structural configuration of a pressurized composite cylinder. This indicates that a mechanism does exist by which the path of damage can be altered in composite structure. The next step is to fully arrest the damage. Before proceeding to this next step, the previously tested configurations of Reference 4 were structurally analyzed to determine the differences amongst them. Particular attention was paid to the stiffness and stress fields as a function of the propagating damage in an attempt to identify the mechanism(s) that redirect propagating damage. Once these mechanisms were identified, graphite/epoxy cylinders of various structural configurations were designed that isolated the identified mechanisms and thus allowed further testing of the mechanisms.

The specimens considered in the work are cylindrical as was considered in the previous work. They were manufactured in an autoclave using techniques previously developed in the laboratory. Testing took place in a blast chamber where the composite cylinders are pressurized with nitrogen gas with an endcap system specially designed for this work [5]. Strain gages were placed in appropriate locations to monitor important strain effects especially local bending which is important in the response of pressurized cylinders [6,7]. After testing, these configurations were carefully analyzed. Specific items considered include the local stiffness (changed via the laminate layup and the composite material utilized), the location of the damage, the local curvature, and various skin-stiffener arrangements and joining techniques including the lack of stiffeners. As various skin/stiffener arrangements were developed, concomitant manufacturing techniques were developed. In addition to the cylinders, tensile coupons were manufactured and tested as needed in support of the work --

mainly to provide baseline strength data including the response of the material and laminate configuration in the presence of notches.

In all cases through this multi-year effort, the experimental work was supplemented and guided by analytical and numerical work. This work provided detailed information on items such as localized stress fields. This was used in conjunction with experimental results to identify specific mechanisms and other issues that required further investigation so as to determine their effects on the damage issues. Various techniques were utilized in this work with much of the numerical work relying on finite element models especially the STAGS (STructural Analysis of General Shells) finite element code available at the Structural Mechanics Branch of NASA Langley Research Center [8]. This was a key item in the interaction between personnel at M.I.T. and at NASA Langley and in the interchange of ideas and results.

The later experimental, analytical, and numerical work in the program was determined after consideration of this initial exploratory phase. The results from this first area of work were carefully considered and also compared with previous reported results. Rules of thumb for design were formulated and further tested in experiments. Later work was planned on damage resistance and damage tolerance facets of the damage issue, again considering the same factors as previously mentioned and utilizing similar experimental techniques as well as developing other experimental techniques as mandated by the specific issues.

Damage in this work was initially introduced as through-cracks. However, other types of damage were considered including delamination and other damage combinations that typically occur due to impact or other events. It is recognized that through-cracks do not represent realistic damage to composite structures in service. However, a through-crack is a well-defined damage state and was used initially to determine the important operative mechanisms in damage arrest and in damage tolerance. Once the mechanisms have been identified, the more realistic damage states were to be considered. An ultimate goal is to work on the issues related to impact damage and thereby link the issues of damage resistance and damage tolerance for the key design issue of impact [2].

Once the mechanisms and parameters were identified, their effects as they are changed were to be ascertained so as to determine design methodologies for composite fuselages. Of particular importance are scaling and structural tailoring. Whereas the finite element method is useful in the identification of mechanisms and in point and final design, emphasis was also placed on developing more time-efficient analyses and approaches suitable for preliminary design stages. These analyses are to incorporate the physics of the problem determined through the earlier work. It is intended that the analyses will thus give the designer a "feel" for the problem as well as allowing the designer to run a number of parametric studies so that the most effective design can be achieved.

WORK, RESULTS, AND IMPLICATIONS

Preface to Section: As is generally the case of work done at educational institutions, this work was conducted primarily as graduate student thesis work. During the duration of this effort, six graduate students worked on and completed theses. In addition, numerous undergraduate students were involved in the research effort. The details of the work, complete literature reviews, approaches, experimental specifics, full presentation and discussions of results, implications, and conclusions and recommendations, can be found in these theses by A.J. Sawicki (S.M.), C.U. Ranniger (S.M.), S.M. Priest (S.M.), H.T. Budiman (Ph.D.), B.L. Wardle (Ph.D.), and A.E. Gruszka (S.M. - pending). A chronological summary of the major aspects of the work on a year-by-year basis is provided here. The interested reader can find the particular details within the theses as well as within published papers based on this work. Both the theses and the papers are listed in the appendix containing the list of published reports and papers.

Year 1

The work in Year 1 centered on the structural configuration of Reference 4 to determine the reasons that the crack propagation behavior is different for the various configurations. Based on this previous work, a test program utilizing plates and cylinders was developed to isolate damage propagation mechanisms. The specimens hasd a base laminate of $(0,45)_s$ graphite/epoxy fabric (Hercules A370-5H/3501-6) with strips of Hercules AS4/3501-6 unidirectional tape used as integral stiffeners.

Nine plate specimens, 203 mm in width and 712 mm in overall length, were fabricated with three different stiffener configurations dealing with the placement of the stiffening strips through-the-thickness. All plates had centrally located through-cracks. For each of the three configurations, three crack length/stiffener width combinations were investigated. The specimens were instrumented with strain gages and photoelastic coatings and tested to failure. Finite element analyses of these configurations were also conducted.

The results from the finite element analyses and the experimental moiré fringe data from the photoelastic coatings indicate a possible influence on damage propagation due to the change in magnitude and orientation of the principal strains ahead of the damage caused by local bending at the stiffener/base plate interface. An examination of the failure modes of the stiffened plates tends to support this finding since in all cases the damage continued into and across the stiffener at specimen failure. The conclusion reached is that the local strain field region ahead of the damage is the controlling factor in subsequent damage propagation. Furthermore, the membrane and bending stiffnesses in this region must be accounted for in any structural analysis used to predict failure.

Nine cylinders, 304 mm in diameter and 609 mm in overall length, were fabricated and tested. The same stiffener configurations as for the plate specimens were used. Three through-crack lengths were included. Finite element analyses of these specimens were also conducted.

Due to the configuration of the specimens and the use of internal pressurization for loading, the sealed specimens are tested under biaxial tension (with a two-to-one ratio of hoop to longitudinal stress). For these cases, predictions of far-field hoop membrane failure stress agreed well with established failure correlations and the developed methodology for notched composite cylinders [3]. All of the cylinders exhibited damage bifurcation as the damage approached the endcaps. All of the stiffened cylinders exhibited damage redirection as the damage reached the stiffened regions. Furthermore, in all cases, the stiffeners redirected the damage subsequent to any bifurcation. It is believed that the differences in local bending stiffness due to stacking sequence and the asymmetry of the fabricated laminate account for the differences in bifurcation location and extent to which damage runs into the stiffeners. The analytical results seem to indicate that the mechanism by which damage may bifurcate in both the unstiffened and stiffened cases is a result of the angular changes in maximum tensile strain orientation near the advancing edge of the damage. What makes these results interesting is the implication that the mere presence of the stiffeners does not affect the fracture behavior but it is the stiffener influence on the orientation of the principal strain field in the region of the damage that affects the damage propagation.

The experimental work had shown that the latest prepreg used at that time for building the specimen appeared to exhibit different basic ply properties. The fabric prepreg purchased for that work was fabricated via a solvent process and is designated A370-5H/3501-6S (with the 'S' indicating 'solvent'), as opposed to the previous material that was impregnated via a hot melt process. A material test program was formulated and conducted to provide the proper ply data for use in the analysis.

Year 2

In Year 2, the work centered on furthering the investigation of the mechanisms and factors identified in Year 1 with regards to damage propagation and damage arrest. A comprehensive discussion of this work was produced in an S.M. Thesis by A.J. Sawicki entitled "Damage Tolerance of Integrally Stiffened Composite Plates and Cylinders" (TELAC Report No. 90-17).

The analysis begun in the past year to better understand the phenomena observed in both the plates and cylinders was continued. This included more refined finite element models to account for stacking sequence and curing variations in both the plates and cylinders that were not incorporated in the initial analysis. Further details on the results of this analysis, the experiments, and the comparison of these can be found in the papers by A.J. Sawicki, M.J. Graves, and P.A. Lagace entitled "The Failure of Integrally Stiffened Graphite/Epoxy Panels" (TELAC Report No. 91-7) and by M.J. Graves and A.J. Sawicki entitled "The Failure of Integrally Stiffened Graphite/Epoxy Cylinders" (TELAC Report No. 92-16).

An experimental program was begun extending the testing to include the influence of radius of curvature and stacking sequence in the base laminate as well as stiffener configuration and material form on damage propagation. In particular, base laminates using AS4/3501-6 graphite/epoxy tape in laminate configurations of $[\pm45/0]_s$ and $[\pm45/90]_s$ have shown that the predictive capabilities established for the quasi-isotropic fabric cylinders must be modified to account for the failure modes and orthotropy of the tape laminates. The $(0,45)_s$ quasi-isotropic fabric laminates, for example, have been shown to be special cases of a more general cylinder failure model.

A more complete understanding of the influence of stacking sequence, material form, and geometry on the failure of pressurized composite cylinders as compared to flat plates was being pursued. In particular, tape quasi-isotropic laminates, $[\pm45/0/90]_s$, were being tested to compare with the $(0,45)_s$ fabric laminates. This information was to be used to guide the formulation of a further test program to further investigate the predictive capability of these models and allow for the creation and verification of analysis tools incorporating the effects determined to be important in the design of composite fuselages.

Year 3

The work in this year centered on further identifying the mechanisms controlling damage initiation and arrest. In particular, the effects of radius were considered via experimentation on cylinders with a quasi-isotropic layup of $(0,45)_s$ fabric laminate configuration. Two different cylinder diameters were tested: 152 mm and 304 mm. The work showed that the developed methodology was able to properly account for the effect of radius and thereby was able to properly predict the failure pressure of these cylinders. This work was documented in the report by C.U. Ranniger entitled "Effect of Cylinder Diameter on the Damage Tolerance of Graphite/Epoxy Cylinders with Axial Notches" (TELAC Report No. 91-10).

The influence of structural anisotropy on the failure pressure and failure mode was further investigated based on the cylinder configuration and experiments initiated in the previous year. This work on cylinders with a diameter of 304 mm using the tape layups $[\pm 45/0]_s$ and $[0/\pm 45]_s$ indicated failure pressures higher than those predicted using the established shell correction factors and effectively higher than flat plate behavior in at least one case. Possible parameters neglected by the existing predictive methodology included structural coupling in the laminates and the biaxial loading inherent in the pressurized cylinders. Also, examination of specimen damage indicated that cylinder fracture modes are different between the fabric and tape material forms. As was the case for the fabric cylinders, however, circumferential stiffening plies were shown to redirect damage propagation and contain damage in the center section of the cylinder away from the endcaps. A quantitative assessment of stiffener effectiveness in containing damage, based on cylinder radius, slit size, and bending stiffnesses of the laminates was proposed. Exploratory experimental work incorporating longitudinal stiffening plies, in addition to the circumferential stiffening plies, indicated complete damage containment is possible.

The details of the work on the influence of the structural anisotropy on the failure pressure and failure mode of pressurized cylinders is summarized in an S.M. thesis by C.U. Ranniger entitled "Damage Tolerance and Arrest Characteristics of Pressurized Graphite/Epoxy Tape Cylinders" (TELAC Report No. 91-11). this work was further presented and summarized in the paper by C.U. Ranniger, P.A. Lagace, and M.J. Graves of the same title (TELAC Report No. 93-4).

Year 4

Work progressed in two areas during Year 4. With regard to damage tolerance, a number of specimens were manufactured from tape prepreg and subsequently tested. The results of this work have better identified some of the possible key parameters and mechanisms that make the behavior of both anisotropic and quasi-isotropic tape cylinders different from the quasi-isotropic fabric cylinders previously tested. One key issue is the splitting along the fiber direction in a ply that can occur in tape laminates but is naturally restricted in woven fabric due to the nature of the weave. This splitting can cause important failure in the circumferential direction that may allow the axial (i.e. longitudinal) stress to play a more important role in the failure. In the methodology used for the quasi-isotropic fabric cylinders, the axial stress is not considered.

In order to better understand the role of splitting and the axial stress in the failure behavior, a set of experiments to test internally pressurized cylinders under only circumferential stress was planned. This required the design of a jig to carry the axial load and thereby relieve the axial load normally carried in the cylinder under pressurization with endcaps and no external fixtures. Construction of the jig began during this year. Tests of laminate and cylinder configurations conducted in the previous work, where a biaxial state of stress has existed, were planned for this configuration with only uniaxial load. The results of these two sets of tests were to be compared in an effort to determine the role of the axial load.

Work in the area of damage arrest progressed on two fronts: experimental and analytical. Analytically, more refined finite element models had been and continued to be developed and run to determine the exact stress and strain fields as the damage progresses towards the stiffening bands. Once again, the purpose of this work was to compare results of cases where the damage does turn versus where it does not turn and identify the key parameter(s) governing this ability to turn the damage. At this point in the work, several analyses had been run, but the results had not yet been carefully analyzed. Experimentally, work had begun on introducing longitudinal stiffening bands onto cylinders in addition to the circumferential bands previously used. In the previous work, the cylindrical stiffening bands have been able to turn the damage but not stop it completely. This work is looking at various longitudinal stiffening band configurations to find ones that will completely arrest the damage. This had not yet been accomplished although a couple of the configurations had stopped all but one of the four bifurcated damage paths. This work continued and eventually the analysis was to be utilized to further define the parameters that make full damage arrest possible.

Year 5

In the Year 5, work progressed in the experimental, analytical and numerical areas. In the experimental aspects, two sets of issues and associated work were pursued. In the first part of the work, experiments continued from the previous year to consider the effects of the axial load on the failure of pressurized cylinders with axial slits. The special text fixture designed in the previous year was manufactured to test these pressurized cylinders under a state of only uniaxial (circumferential) stress.

The methodology to predict cylinder failure, which was developed and shown applicable for quasi-isotropic configurations, was used in order to further assess the limitations of this methodology. A previous limitation demonstrated was for structurally anisotropic configurations and this was further considered here. In all cases, the methodology was not able to predict the failure pressures of the uniaxially-loaded cylinders. This was most marked in the case of the structurally anisotropic cylinders. Furthermore, in all cases the failure pressures for the case of uniaxial loading fell below those for the same configuration under biaxial loading. Such differences were again most marked for the structurally anisotropic cases. Examination of the fracture paths and overall failure modes showed that the largest differences in the failure pressures occurred for those cases with the least match in failure mode with the coupon specimens tested in tension from which the basic response to the presence of the notch was determined. Strain gages placed near the notch tips showed that subcritical damage occurred in all cases. Previous work on coupons has indicated the importance that such damage can play in the overall failure response.

These results coupled with previous work thus show that failure is controlled by local damage mechanisms and the subsequent stress redistribution and damage accumulation scenario. It is therefore important to understand the local behavior in order to assess the role of various parameters and to predict the failure of composite structures. Careful analysis must be performed to determine the local stress state. This modeling must include the considerations of the global structural configurations and its effects on the local stresses as well as the local details including progressive damage that occur. Such stress analyses must then be utilized with reliable failure criteria for various damage mechanisms that occur in composites and their structures. In addition, experimental progressive damage studies need to be conducted so that the subcritical damage states that exist can be documented and compared with predictions from the stress and failure analyses.

These results also show that predictive methodologies that use global/averaging parameters to try to capture local damage behavior from coupon data cannot properly account for the details of the local behavior and thus will not be able to predict failure except in cases where the damage modes and fracture paths leading to final failure do not change between the coupons and the structure. This clearly indicates that the use of such correlative methodologies with "scaling" factors and analyses, such as those represented by the "building block approach", are good engineering tools at this time (still true today) when the deficit in understanding demands tools that are overly conservative in order to provide a safe structure. However, such tools cannot hope to provide the design capability to utilize composite materials to their full effectiveness. Composites and their structures need to be treated at the level where their key mechanisms are operative and further work in this program was oriented to concentrate on such details. This was done to lead towards a true understanding and predictive capability for failure, and thus damage tolerance, of composite materials and their structures such as fuselage structures.

This set of work is documented in greater detail in an S.M. thesis by S.M. Priest entitled "Damage Tolerance of Pressurized Graphite/Epoxy Tape Cylinders Under Uniaxial and Biaxial Loading" (TELAC Report No. 93-19). Further discussion of this work is provided in a paper by P.A. Lagace and S.M. Priest of the same title (TELAC Report No. 95-5).

In addition, during this year experimental work was conducted for further consideration of arrest mechanisms and capability. In particular, five axially and circumferentially-stiffened cylinders were manufactured. In one cylinder, unidirectional tape layers were used for the axial and hoop stiffeners. In all other cases, different stiffener configurations of fabric were used. Several cylinders had a "checkerboard" (or continuous) stiffener configuration where there were no ply-overlaps at the junctions between the axial and the hoop stiffeners. This configuration was chosen based on the post-mortem inspection of the first cylinder tested where delamination was observed at the junctions between the axial and hoop stiffeners as damage propagated. To alleviate this problem, continuous stiffener construction was proposed.

Analytical and numerical work continued during the year with an emphasis on understanding the mechanisms responsible for the damage tolerance behavior and damage propagation and containment characteristics of the stiffened cylinders. Preparation was done for the nonlinear analysis of the test specimens using the STAGS finite element code available at NASA Langley Research Center. The doctoral student involved in this aspect of the work spent one week at NASA Langley learning how to work with STAGS. Work began to analyze the cylinder with a diameter of 305 mm and different slit sizes to study the influence of slit size on the degree of geometric nonlinearity exhibited in the structural response.

Year 6

During Year 6, two main areas of work were addressed. The first is the continuation of the experiments and subsequent analysis and consideration of the results on the damage propagation work involving the pressurized composite cylinders with axial and hoop stiffeners of various configurations including the "checkerboard" configuration noted in the previous year. The results show that the stiffening elements in the hoop direction are more effective in redirecting damage than those in the axial direction. Damage continues its propagation in the hoop direction despite the presence of axial stiffeners although the damage is generally arrested at a second set of axial stiffeners. These resulted continued to be considered during the year.

The second main area of work addressed the issue of geometric nonlinearity in the response of pressurized cylinders. In the work to date, the failure prediction methodology for axial slits was utilized and extended. However, this methodology considers only linear phenomenon. The methodology is based on the correlation of in-plane tensile coupon data as modified for structural effects in the cylinders. The structural effects taken into account are due to different structural responses of cracked plates and shells when loaded perpendicular to the crack, particularly the bulging behavior that occurs due to a combination of internal pressure and geometric-coupling. This bulging behavior causes the stress intensity in shells to be higher than that in flat plates and was accounted for via a linear analysis [7]. However, localized large deformation can result in geometric nonlinear response. Work in the literature on this phenomenon [e.g. Reference 9] are all case-specific. Thus, work was conducted on this nonlinear phenomenon to characterize the *general* response and involved numerical and experimental portions.

The STAGS finite element code was used extensively to analyze the linear and nonlinear responses of different shell configurations. The stress intensification was computed using the nodal-release technique. Initial work was done to validate the numerical approach. Numerically computed stress intensification factors were computed for a linear problem and compared with known results. This resulted in a choice of an appropriate crack increment for the node-release technique to yield an error of less than 1%.

Once the approach was validated, the effects of geometric nonlinearity on the cylindrical specimens with a diameter of 304 mm tested to date in the program were investigated using the numerical analysis. The nonlinear prediction for the stress intensification and the resulting prediction of the failure pressure by modifying the methodology to include the nonlinear stress intensification factor showed a difference of less than 10% between the linear and nonlinear results for all cases tested to date. These results confirm the good agreement observed between experiments and linear predictions for this specific laboratory-scale geometry.

The work then progressed to approach the generic problem. As previously noted, work reported in the literature has shown that these nonlinear effects can be important in specific instances. To address this in a generic way, the Donnell-Mushtari-Vlasov nonlinear shallow-shell equations were initially used due to their relative simplicity. Using nondimensionalization techniques, it can be shown that the governing equations depend on two parameters that rely on the crack half-length, the cylinder radius, the cylinder thickness, the applied pressure, and the Poisson's ratio and modulus of the material (or baseline laminate, in this case). One parameter is used to characterize the linear solution. Note that the same two parameters can also be obtained from the more complicated nonlinear Sanders' shell equations [10]. The second parameter can be obtained from a physical argument and is a measure of the "driving force" of the nonlinearity. This "driving force" is directly proportional to the hoop stress (involving pressure, radius and thickness) since the higher the stresses, the more nonlinear the response. The parameter is inversely proportional to the material (laminate) stiffness since the stiffness is a measure of the material resistance to deformation. And the parameter is also inversely proportional to the shell parameter (of thickness divided by radius) since the smaller this ratio, the more bending, and therefore more nonlinear deformation, is expected. By combining these three items of hoop stress, material stiffness, and shell parameter, the same expression for the parameter is obtained.

In order to verify the applicability of the two parameters to characterize the dependence of the stress intensification factor with pressure in axially-cracked cylinders, finite element models of different cylinders were created with four different values of the first parameter ranging from values corresponding to the laboratory-scale specimens tested in this program up to that representing the geometry of an actual fuselage structure of a medium-sized transport airplane, such as the MD 80, with a diameter of approximately 3 meters. The nonlinear dependence with pressure of the stress intensification of the different cylinders as represented by these different values of the first parameter is highly dependent on the shell geometries. However, when the stress intensifications are plotted as functions of the second parameter, the nondimensional loading parameter, all the results collapse to a single curve. This indicates that that second parameter is indeed a proper nondimensional parameter to characterize the loading.

The work was then extended to find a means to present the nonlinear results in an easy-to-use format (e.g. design chart utilizing these parameters). The metric used is the percentage error between the linear and nonlinear solutions for the membrane stress intensifications. An iso-nonlinear-error plot was chosen as the means. This plot shows lines depicting constant values of the percent error between linear and nonlinear solutions with the two nondimensional parameters plotted along the axes. Knowing cylinder geometries (cylinder radius, thickness, and crack length), material properties (Young's modulus and Poisson's ratio), and loading condition (operating pressure), one can then compute the two controlling parameter and use this plot to determine the error associated with using the linear solution. These results show that the error for the laboratory-scale specimens to date is small (less than 10%). However, the error becomes significant for a typical Boeing fuselage 737 fuselage. The important values for that case are a radius of approximately 2 meters, a skin thickness in the range of 1 to 2 mm, an operating pressure at cruise condition of about 55 kPa, and a maximum sawcut length of 300 mm. The error of using the linear solution is predicted to be between 15% and 40%. It was therefore concluded that geometric nonlinearity is an important structural scaling effect in the failure of such structures as different degrees of nonlinearity exist at different scales. The details of this work are presented in a paper by H.T. Budiman and P.A. Lagace entitled "Nondimensional Parameters for Geometric Nonlinear Effects in Pressurized Cylinders with Axial Cracks" (TELAC Report 95-7).

Experiments were conducted on two cylinders to verify the nonlinear analyses performed. The standard configuration used in the program work was utilized with one laminate having a layup of $(0,45)_s$ and the other $(45,0)_s$. Both were made from AS370-5H/3501-6 graphite/epoxy fabric. Both laminates are quasi-isotropic and have the same in-plane stiffness. However, the second laminate has a different bending stiffness from the first so that the effects of different bending stiffness on the degrees of nonlinearity in the strain readings could be assessed. Three different slit sizes were used. Regions where significant differences between the strain fields of the linear and nonlinear solutions were identified and selected for strain gage location on the cylinders. Five strain gages were used on each cylinder. Tests were run to only 60% of predicted failure pressures so that cylinders could be reused. These experiments were completed just as the year had ended and the results were to be analyzed and compare with the results from the finite element analyses.

Year 7

In Year 7, work continued on several fronts. The first dealt with the cylinders tested at the end of the previous year with measurements made of strain via strain gages in regions where the linear and nonlinear solutions for the stress/strain field indicated significant differences. These results were carefully considered and compared with the nonlinear solutions. The numerical results were able to correctly predict the measured pressure-strain responses. There were some discrepancies, but this can be explained by the sensitivity of strain gage placement and the high gradients associated with the strain fields. The observed experimental responses can be explained as (local) manifestations of the interplay of the geometric nonlinearity effects on the bending and membrane components of the strain response and how this interplay changes with increased pressure due to the changing nonlinear behavior. One particular phenomenon of importance noted in the course of the work was the role of membrane-stiffening actions to reduce significant strain gradients, particularly "wells" in the strain field. This leads to the total strain distribution becoming more and more shallow as pressure increases due to these geometric nonlinear effects. This is particular noteworthy in the vicinity of the slit tip where the linear solution indicates a very high value of the total strain at the slit tip. The strain decreases rapidly, reaches a minimum (compressive) value, and then increases again before finally reaching its far-field value in the linear solution. This "well" in the total hoop strain distribution is formed due to the significant bending gradient in the region near the slit tip. As the nonlinear effects become more important (e.g. as pressure increases), this total strain distribution becomes more and more shallow. This clearly shows the inability of linear analysis to predict the actual behavior.

The second area of work dealt with further consideration and associated analysis of the cylinders tested in previous years of the programs in order to assess the combined effects of axial and hoop stiffeners on the damage propagation in pressurized composite cylinders with axial slits. This included the continuous "checkerboard" configuration of axial and hoop stiffeners. The failure of all cylinders were consistent with the failure prediction methodology used and further developed in the program. In all the cylinders tested, the first set of axial stiffeners were unable to completely arrest damage after the damage had turned at the hoop stiffeners. The elimination of the matrix crack path in the continuous "checkerboard" configuration eliminated the delamination that occurred when axial and hoop stiffeners were overlaid and a matrix crack running at the junction induced the delamination. However, eliminating the matrix-crack path did not help arrest damage at the first set of axial stiffeners. However, the damage that was successfully turned by the hoop stiffeners was generally arrested at a second set of axial stiffeners. It can therefore be concluded that the axial stiffeners, which have zero curvature, are not as effective as the hoop stiffeners that have roughly the same curvature as the base cylinder. These experimental observations are consistent with previous analytical work [11] that shows that the hoop stiffeners are more effective than axial stiffeners in affecting the stress intensity factor in metallic cylinders due to importance of stiffener curvature in influencing the stress fields near the slit tips (the higher the curvature, the more effective the stiffener is) [11].

It is furthermore important to consider the driving force during different stages of damage propagation in considering the relative effectiveness of hoop and axial stiffeners to arrest/redirect damage. The overall damage propagation can be separated into two stages: one, before the first bifurcation takes place when damage initially propagates in the axial direction and, two, after the first bifurcation in which the bifurcated damage turns and continues its propagation in the hoop direction. In the first stage, damage propagates in a relatively self-similar manner with the cylinder hoop stress as the scaling/driving parameter. This stage of damage propagation includes the bulging phenomenon [6]. The second stage of damage propagation is caused by the flapping phenomenon as induced by internal pressure [12]. This can be thought of as the bending of a cantilevered plate under uniform pressure loading.

A first-cut engineering model was proposed based on dimensional argument to determine the proper scaling/driving parameter after flapping occurs. The phenomenon is modeled, as noted previously, as the bending of a cantilevered plate under uniform pressure loading. The moment taken at the tip of the damage propagating in the hoop direction is proportional to the pressure and to the square of the distance the damage has run in the hoop direction. When the damage tip reaches the axial stiffeners, this flapping distance is proportional to the square of the spacing of the axial stiffeners. Based on elementary beam/plate theory, the bending stress is related to the moment, the thickness, and the moment of inertia. Using these two items, it was shown that the bending stress can be expressed as the pressure times the square of the ratio of the spacing of the axial stiffeners to the thickness of the cylinder. As flapping occurs, the driving force (pressure) can decrease due to bending of the crack face which allows the pressurizing gas to leave the cylinder. This was noted as the likely reason for the observed damage arrest at the second set of axial stiffeners on these cylinders.

There are therefore two separate physical problems that influence damage propagation and arrest in pressurized composite cylinders. The first physical phenomenon is the bulging phenomenon that governs the damage propagation before the first bifurcation. The scaling/driving parameter for this phenomenon is the hoop stress that involves the pressure, the cylinder radius, and the cylinder thickness. The effects of bulging on different cylinder geometries depend on the cylinder radius and thickness and are accounted for in the failure prediction methodology [4]. The second physical problem that is important only after the first bifurcation has taken place is flapping [12]. Flapping is governed by the bending stress and involves the pressure, the axial stiffener spacing, and the cylinder thickness.

This work is more fully documented in a paper by H.T. Budiman, K.F. Henault, and P.A. Lagace entitled "Effects of Axial and Hoop Stiffeners on the Damage Propagation in Pressurized Composite Cylinders" (TELAC Report 96-1). Furthermore, the work showed the potential pitfalls in using a subscaled specimen to study both damage propagation and arrest. Before bifurcation, the proper scaling parameter is the hoop stress of the scaled and actual cylinders. After bifurcation, the scaling/driving parameter of interest is the bending stress. Simple calculations for the cylinder in this program as compared to a medium-sized transport aircraft (e.g. Boeing 737) indicate nearly a full order of magnitude difference in these two scaling parameters. From this comparison it is clear that it may not be possible to properly simulate/scale both the bulging and flapping phenomena in an experiment on a single subscaled specimen as different scaling parameters govern the two phenomena. This is thus one of the reasons why arrest by the axial stiffener was more difficult to accomplish in the laboratory-scale specimen. By scaling the subscaled cylinder based on the hoop stress, complete damage arrest cannot be achieved in the same specimen.

In a third area of work, the STAGS finite element code was used extensively to analyze the linear and nonlinear responses of different stiffened shell considerations in order to consider the mechanisms involved in the damage arrest and redirection of these configurations. Previously in this program, the stiffening bands had been placed approximately 200 mm apart so that the stiffeners had minimal effects on the stress and strain fields near the slit tips. This previous work therefore did not model the interaction between the propagating damage and the stiffening bands. The work in this year investigated the propagating damage as it approached the hoops stiffeners and thus the interaction between the damage and the stiffening bands.

The geometry of the stiffened cylinders considered was such that the area between the slit tip and the edge of the stiffeners, called the ligament, was set at a constant of 20 mm. This would allow the placement of two strain gages in this area in future planned work. Three different slit sizes were considered. The spacing between the hoop stiffening bands on each size of the slit was therefore different as it depends on the slit size. The ratio between the ligament length and the half-crack length, a key parameter, is different for each case. This analysis, and the subsequent planned experiment, can therefore be thought of as a model of a growing damage as damage approaches the stiffening bands (using the nondimensional parameter of ligament length to half-crack length). The stiffening bands were made of four 0° fabric layers and were therefore of the same thickness as the unstiffened base cylinder with a $(0/45)_s$ quasi-isotropic laminate configuration. The numerical results obtained in the past year indicated that far from the stiffeners (i.e. at the center of the cylinder), the stiffened and unstiffened solutions are almost identical. However, the effects of the stiffening bands are more apparent in the axial strain distribution, particularly in the ligament area. Nonlinear analysis was performed in all cases.

Finally, consideration was also given to begin work on damage resistance under this effort and that this be coupled with work sponsored by the Federal Aviation Administration (FAA). During the previous several years, TELAC had a research program with the FAA to consider the impact behavior of composite structures. This work looked both at the damage resistance and damage tolerance of flat, monolithic laminate configurations. The work most recently concentrated on the damage resistance aspect of the issue since it became clear that it is necessary to define the exact three-dimensional damage state in order to properly assess the damage tolerance properties [13]. This damage resistance work had progressed to the point where it could interface with the fuselage work. To date, the fuselage work had looked at man-made through-notches in order to begin to understand the basic issues and mechanisms involved in the damage tolerance and damage arrest of the pressurized cylinders. The ultimate goal, however, has been to look at realistic service damage such as that created by an impact event. In the same manner, the FAA work looked at relatively simple structural configurations in order to identify basic mechanisms that affect impact damage resistance. The ultimate goal of that work was to define the damage that occurs in order to then assess damage tolerance of typical aircraft structural configurations. These two pieces of work thus approach similar problems from opposite ends and had reached the point where significant synergy could be gained by some combination of the research efforts. The next logical step in the damage resistance work was to conduct tests on curved specimens in order to assess the effects that curvature has on impact damage resistance and the mechanisms involved in the structural response. Once an understanding of the damage and the mechanisms was obtained, then appropriate damage could be considered in damage tolerance and damage arrest tests. Consideration was given to this during the year.

Year 8

The main accomplishment during Year 8 was the completion of the Ph.D. thesis by H.T. Budiman entitled "Mechanisms of Damage Tolerance and Arrest in Pressurized Composite Cylinders" (TELAC Report 96-7). This report described in detail much of the analytical, numerical, and experimental work on the mechanisms of damage tolerance and damage arrest in pressurized composite cylinders conducted under this grant sponsorship over the past several years.

The experimental and analytical work continued from the previous year on the model of propagating damage by using the specimens with a fixed ligament length (from the tip of the slit to the edge of the stiffener) of 20 mm. The experimental work was completed, as was the numerical analyses, and the results compared. The nonlinear finite element results showed a strain field with high gradients due to the interaction of the effects of the slit and the stiffening band. The strain attains a high value at the slit tip, initially decreases, reaching a minimum value, and then increases again near the edge of the stiffening band due to bending. This "well" thus develops in the longitudinal strain distribution in the stiffened case with a concomitant rise in the strain level at the stiffener edge. The longitudinal strain may cause damage to turn 90° from its original propagation path. The existence of bending induced by the presence of the stiffening band is thus indicated. This bending is caused by membrane and bending stiffness discontinuities between the unstiffened and stiffened regions and is expected to be proportional to the difference between the two regions. These numerical results provide a justification of the previously proposed (empirical) containment ratio [14], which is based on the bending stiffness ratio between the stiffened and unstiffened region, in characterizing stiffener effectiveness in damage bifurcation.

The interaction between the stiffening band and the geometric nonlinearity on the magnitude of the nonlinear stress intensification factor was also assessed as damage propagated and approached the stiffening band. These effects can also be used to assess the same effects on the hoop stress distributions. In the case of linear analysis, the linear value of the stress intensification factor is reduced by 10% to 15% and thus the difference between unstiffened and stiffened values is relatively insignificant. However, this changes with the inclusion of nonlinear effects. For the nonlinear case, the value of the stress intensification factor increases as it does for the linear case, but the rate of increase decreases as damage grows towards the edge of the stiffener. This reduction in the magnitude of the stress intensification implies a similar reduction in the hoop stress and strain close to the slit tip. This relative "stiffening" response due to nonlinear effects may therefore alter the magnitude and orientation of strain in the ligament region ahead of the slit tip and may be part of the mechanism that causes damage to turn. This phenomenon deserves further investigation and should include consideration of the *T-stress* concept used as a crack stability criterion by Cotterell and Rice [15].

During this year, work was begun to numerically calculate the stress intensification for configurations that have been tested in past years including $[0/\pm45]_s$ and $[\pm45/0]_s$ orthotropic configurations as well as quasi-isotropic $[0/90\pm45]_s$ and $[90/0/\pm45]_s$ configurations that have bending-twisting coupling since they are made of unidirectional tape rather than fabric prepreg. These configurations have also been tested in the configuration where they have only uniaxial stress. The numerical calculation of the stress intensification was being pursued in an attempt to further extend the damage tolerance methodology utilized in this work. The general concept of accounting for the local stress intensification due to the localized bending in the vicinity of the damage (the intensification of the membrane stresses occur via the bending-stretching coupling present in shell structures) should be valid for general configurations. The specific equation used in the past work was derived for isotropic configurations and was found to not apply in the general cases. The challenge is, therefore, to find appropriate parameters for orthotropic configurations.

In the area of damage resistance, consideration was being given to the existence of an instability in the response of composite shells. This results in dramatic differences in both structural and damage response as compared with plate structures. Modeling of the shell response also incurs additional complexities as both bifurcation and limit point buckling must be captured, as well as postbuckling (instability region and second equilibrium path). The elastic response, particularly buckling, is extremely important in evaluating the impact damage resistance for shell structures [16]. Damage resulting from impact has been found to depend on not only the magnitude of the peak force, but on which equilibrium path the peak force occurs. Thus, understanding and calculation of the elastic response parameters (e.g. the critical snapping load and the deformations associated with it) are seen as crucial in assessing the impact damage response of composite shell structures, such as fuselages. It is important to understand the damage resistance behavior of shells in order to properly determine the type(s) of damage that must be addressed in damage tolerance and damage arrest studies. Thus, in the past year work had begun on preparation for modeling of the response of composite shell structures to transverse loading using the STAGS finite element capability.

Year 9

Work continued on two main fronts during Year 9. The primary accomplishment was in the area of damage resistance where the experimental work and numerical modeling was completed on the buckling of transversely-loaded composite shells including the role of this phenomenon in the damage resistance of these structures. This work was summarized in the Ph.D. thesis by B.L. Wardle entitled "Buckling and Damage Resistance of Transversely-Loaded Composite Shells".

The shell structures examined in this work were monolithic laminated graphite/epoxy structures having geometric characteristics and boundary conditions representative of a commercial transport fuselage. Load-deflection and mode-shape results were utilized to characterize the composite shell response that includes bifurcation, limit-point buckling, dynamic collapse, and three distinct stable equilibrium paths. The effects of specimen thickness (three thicknesses) and axial boundary condition are particularly explored, as well as effects from compliance of the text fixture in the circumferential direction.

The asymmetric meshing technique (AMT) was developed for and used throughout this work for the numerical modeling of the configurations. This technique involves introducing slight imperfections in the structure in induce instability by asymmetrically meshing the configuration. This results in an asymmetric stiffness matrix. The technique was found to be quite effective in evaluating bifurcation from nonlinear pre-buckling paths for the shells considered in the work. This includes the point of bifurcation, the postbuckling response, and mode-shape evolutions. The technique and associated models were validated by comparison to traditional benchmark analyses and verified by comparison to composite shell data. Advantages of the AMT over traditional techniques for inducing bifurcation in shells include simplicity, efficiency, and robustness.

Bifurcation into asymmetric modes was easily identified in the shell response via mode-shape evolutions acquired during testing. These mode-shape evolutions, coupled with results from the numerical modeling, allowed a much clearer interpretation of the experimental loading response than would otherwise be possible. In particular, these comparisons allowed a premature transition to an adjacent bifurcation path to be identified in the experimental data. Given the numerical results, the most probable explanation is that a geometric or loading imperfection (likely an asymmetry) induces the transition to the secondary path to occur early. This conclusion was supported by analysis wherein a geometric imperfection is included in the shell model and the early transition is achieved.

Comparison of the experimental and numerical load-deflection responses showed that, in general, the experimental response was more compliant than the predicted response. This is expected due to experimental effects such as transverse shear, damage, and test fixture compliance which are not included in the models. In particular, test fixture compliance at the hinged circumferential boundary may induce a more compliant experimental response, delay or eliminate bifurcation, and promote a symmetric limit-point response. The effect of test fixture compliance was more pronounced for thicker specimens because the relative stiffness of the specimen to that of the test fixture increases. Modeling refinements such as the inclusion of transverse shear should be explored to obtain improved predictive capability. A second boundary condition effect was explored by comparing experimental and numerical results for shells with either free or simply-supported axial edges. Shell response prior to bifurcation of the axially-free shells were in excellent agreement. In general, however, the response of the axially simply-supported shells was more complicated, involving multiple critical points and/or dynamic collapse as well as higher critical loads than shells with free axial edges. These results are important from a design perspective because the simply-supported axial edges are a more realistic representation of a fuselage than the free edges, but specimens with free edges are oftentimes used as test articles due to their simplicity. It is recommended that the effect of other boundary conditions (such as fully clamped) be explored to bound the possible range of responses, particularly in regard to bifurcation and damage resistance.

No damage atypical of that previously observed for composite plates was observed in this work. This was attributed to the lack of observed asymmetric bifurcation modes in cases where the specimens were damaged. Thus, no direct link could be made between asymmetric bifurcation modes and either asymmetric damage at the loading site (as had been previously observed) or damage away from the loading site. Further investigation of damage away from the loading site, or asymmetric damage at the loading site, due to asymmetric (bifurcation) deformation modes can be guided by finite element analyses of shells where bifurcation is predicted. A important conclusion of the work was that (further) combined numerical and experimental investigations such as that undertaken in the work can ultimately lead to a more refined predictive capability for damage resistance of composite structures.

The second area of work pursued during this year was the calculation of the stress intensification factors for past configurations tested, as described in the previous year, using the STAGS numerical finite element code. This allowed a better representation of the actual behavior of the structural configuration from the analytical expressions used in the original proposed methodology. Preliminary results indicated a better correlation with the experimental results using the stress intensification factors from the STAGS analysis. Based on these results, initial plans were made for a more extensive program to consider these aspects, including the nonlinear aspects previously noted in this work.

Year 10

The work pursued during Year 10 involved a continuation of the damage tolerance considerations from the previous year. Plans were continued to be made on the program noted in the previous year. In particular, consideration was given to the original proposed predictive methodology and that it had been developed, and successfully used, to predict the failure pressure of quasi-isotropic cylinders with through-thickness notches. However, the long term objective of the work is to be able to predict the damage tolerance of internally pressurized composite cylinders such as fuselages. This includes damage running the range from well-defined notches to random damage including that which occurs due to impact. Furthermore, various laminate configurations including orthotropic and structurally anisotropic configurations with various couplings need to be considered. This work addressed the issues involved in extending the predictive methodology to such other cases where the methodology has not been successful.

The plan was divided into two phases. In phase one, numerical analyses of the graphite/epoxy cylinders tested in the past are conducted utilizing the STAGS finite element code in order to better understand the local behavior at the through-notch and how this is affected by loading and laminate configuration. Linear and nonlinear stress intensity factors for mode I were evaluated using the nodal release technique. Results are compared with available experimental data available from the past years and to the failure predictive methodology. The numerical results obtained can predict the failure pressure of quasi-isotropic cylinders including the case of uniaxial loading (which the original methodology could not) but could not generally predict the response of the structurally anisotropic cases although the STAGS results do provide a much better prediction than the original methodology. In these cases, the results from the STAGS models are consistently lower than the experimental ones. A possible factor for the discrepancy is that the applicability of the predictive methodology depends on the similarity of initial fracture modes in coupons and cylinders of the same layup. Such similarity occurs in the quasi-isotropic cases but not in the structurally anisotropic ones. Further numerical analyses were planned where mode II and mode III were also to be evaluated in order to see if their influence is significant in the structurally anisotropic cylinder configurations. Further inclusion of nonlinearity aspects were also pursued. The second planned phase of the work was to look at more generic configurations including general damage.

As of the end of the grant, most of the work on phase one as described above was complete. Due to the termination of the grant, phase two was not pursued. Final analyses and consideration of this work is being accomplished and an S.M. thesis is being prepared by A.E. Gruszka.

Although no further work was pursued during this year on the damage resistance aspects, further consideration was given to the work from the previous two years (as documented in the doctoral thesis by Wardle) and papers were written from this work. Three papers were identified and one completed. The completed paper is by B.J. Wardle and P.A. Lagace and is entitled: "Response of Transversely-Loaded Composite Shells: Bifurcation, Limit-Point Buckling, and Dynamic Collapse". The other two papers are currently in final stages of preparation.

SUMMARY

Work was conducted over a ten-year period to address the central issue of damage in primary load-bearing aircraft composite structure, specifically fuselage structure. This included the three facets of damage resistance, damage tolerance, and damage arrest. Experimental, analytical, and numerical work was conducted in order to identify and better understand the mechanisms that control the structural behavior of fuselage structures in their response to the three aspects of damage. Furthermore, work was done to develop straightforward design methodologies that can be employed by structural designers in preliminary design stages to make intelligent choices concerning the material, layup, and structural configurations so that a more efficient structure with structural integrity can be designed and built.

Considerable progress was made towards achieving these goals via this work. In regard to *damage tolerance* considerations, the following were identified as important effects: composite layup and associated orthotropy/structural anisotropy, specifics of initial local damage mechanisms, role of longitudinal versus hoop stress, and large deformation and associated geometric nonlinearity. Means were established to account for effects of radius and for the nonlinear response. In particular, nondimensional parameters were identified to characterize the importance of nonlinearity in the response of pressurized cylinders. This led to the establishment of a iso-nonlinear-error plot for reference in structural design. Finally, in the case of damage tolerance, the general approach of the original methodology to predict the failure pressure involving extending basic plate failure data by accounting for the local stress intensification was accomplished for the general case by accounting for the mechanisms noted by utilizing the capability of the STAGS finite element code and numerically calculating the local stress intensification for the particular configuration to be considered. For the issue of *damage arrest*, placement of and configuration of stiffeners (including stiffener curvature), and magnitude and orientation of principal strains due to local bending were found to be key considerations. Means were established to account for stiffener effectiveness quantitatively based on radius, slit size, stiffener curvature, and relative bending stiffnesses involved. Geometric nonlinearity was also found to play an

important role here. Furthermore, it was determined that damage propagation is controlled by different mechanisms (hoop stress versus flapping stress and the associated factors involved in each) depending upon the direction of damage propagation. This latter item results in an inability to scale these phenomena in one test due to the different factors involved. Finally, the importance of shell curvature and associated instability in response to transverse loading including impact were found to be important considerations in *damage resistance.* A technique, involving asymmetric meshing of a finite element mesh, was developed to predict this behavior and showed excellent correlation with experimental results.

Further details of these ten years of work are presented herein with references made to the fourteen documents produced during this work where full details can be found. Implications of this work are discussed and recommendations made. Although it is clear that there is more work to be done to fully understand composite fuselage technology and specifically the overall issue of damage in primary load-bearing composite structures, important understanding and capability has been extended via this work.

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APPENDIX:
List of Reports and Publications

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2. A.J. Sawicki, M.J. Graves, and P.A. Lagace, "Failure of Graphite/Epoxy Panels with Stiffening Strips", TELAC Report 91-7, 1991. (also available in *Composite Materials: Fatigue and Fracture, Fourth Volume, ASTM STP 1156*, ASTM, 1993, pp. 5-34)

3. C.U. Ranniger, "Effects of Cylinder Diameter on the Damage Tolerance of Graphite/Epoxy Cylinders with Axial Notches", TELAC Report 91-10, 1991.

4. C.U. Ranniger, "Damage Tolerance and Arrest Characteristics of Pressurized Graphite/Epoxy Tape Cylinders", S.M. Thesis, Massachusetts Institute of Technology, TELAC Report 91-11, 1991.

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