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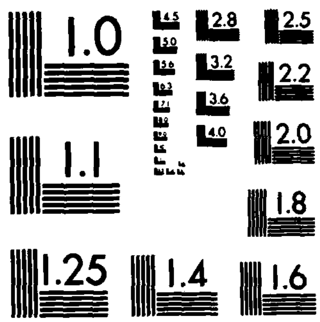

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AFWAL-TR-84-3039

IMPROVING THE BIRDSTRIKE RESISTANCE AND DURABILITY OF AIRCRAFT WINDSHIELD SYSTEMS: PROGRAM TECHNICAL SUMMARY

Blaine S. West

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300 College Park Avenue
Dayton, Ohio 45469

May 1984

Final Report for Period 20 February 1980 - 20 February 1984

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FLIGHT DYNAMICS LABORATORY
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This final report defines the program objectives, presents an abstract for each technical report generated, and lists the major papers and presentations resulting from the technical effort. Major program accomplishments, both generic and specific, are also enumerated.

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FOREWORD

The effort documented in this report was performed by the Aerospace Mechanics Division of the University of Dayton Research Institute (UDRI), Dayton, Ohio, under Contract F33615-80-C-3401, "Birdstrike Resistant Crew Enclosure Program," for the Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. Air Force administrative direction and technical support was provided by Lt. Larry G. Moosman, AFWAL/FIEA through November 1980, and subsequently by Lt. Robert Simmons, AFWAL/FIEA, the Program Managers. The experimental portion of the work was conducted at the Structural Test, Composites and Polymeric Materials, and Impact Physics Laboratories of UDRI. Birdstrike testing was performed at UDRI and at the Arnold Engineering Development Center, Arnold Air Force Station, Tennessee.

The work described herein was conducted during the period from 20 February 1980 to 20 February 1984. Project supervision and technical assistance was provided through the Aerospace Mechanics Division of UDRI with Mr. Dale H. Whitford, Supervisor, and Blaine S. West, Head, Applied Mechanics Group and Project Engineer. The principal investigators were Blaine S. West, Kenneth I. Clayton, Gregory J. Stenger, Richard A. Nash, B. Basava Raju, Andrew J. Piekutowski, and Michael P. Bouchard.

The active support, insight, and technical direction of Ralph J. Speelman, Capt. Walter W. Saeger, Jr., and Richard L. Peterson, AFWAL/FIEA, on this program is gratefully acknowledged; similarly, the guidance of R. Harley Walker and Malcolm E. Kelley, AFWAL/FIER, during the in-service durability survey. In addition, the author wishes to acknowledge the significant contributions of Ralph C. Shelton, T-38 Subcontract Project Engineer at Swedlow, Inc., and J. Donald Locke, F/RF-4 Subcontract Project Engineer at Goodyear Aerospace Corporation. Appreciation is expressed to the Arnold Engineering Development Center test personnel for their cooperation and assistance in successfully completing the required full scale flight hardware instrumentation and testing.

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SECTION 1
INTRODUCTION

This report is comprised of three major sections. Section 1 presents the background and overall program objectives. A compilation of abstracts from the reports prepared and issued to document the program effort, along with a listing of directly related papers presented throughout the contract period, is presented in Section 2. Significant program accomplishments are summarized in Section 3.

1.1 BACKGROUND

Studies of the hazards presented by bird impact on transparencies date back to the early 1940's. Since that time, the potential damage resulting from bird/aircraft collisions has greatly increased. This is principally the result of increased aircraft speeds that result in both increased energy densities and impulsive forces during the impact process. The problem has been further aggravated by the introduction of low altitude, high speed mission profiles. These flight profiles place the aircraft in areas of high bird density at speeds approaching or exceeding the speed of sound. Birdstrikes under these conditions increase the probability of serious aircraft damage which may result in an aborted mission or loss of aircraft.

The Air Force recognizes the importance of protecting its pilots and at the same time reducing the cost of lost and damaged aircraft. It has been found, from past incidents and impact tests, that the engines and transparent enclosures are the most vulnerable portions of an airplane.

Severe damage and loss of life has, unfortunately, not been an uncommon experience since the 1960's. Two commercial accidents in the early 1960's resulted in the combined loss of 79 lives. Since 1966, the U.S. Air Force has lost more than 10 aircraft worth in excess of $61 million due to bird impacts on transparent enclosures. These include the loss of a T-37B with one fatality, three T-38's with two fatalities, two F-100's with one fatality, one F/RF-4 with one fatality, and five F-111's with, fortunately, no fatalities. In addition to the $61 million loss in aircraft and the incalculable loss due to fatalities, an estimated $20 million has been spent in repair costs during the period 1966 to 1972. Further, the role of bird impacts in aircraft losses in South-East Asia is not fully known.

Numerous efforts are currently underway to make U.S. Air Force aircraft windshield systems more resistant to bird impacts. In addition, a number of advanced development programs are being conducted to examine future windshield materials and avoidance concepts. It has become apparent from these studies that the technological base developed during the 1940's, 1950's, and early 1960's for bird resistant design is not adequate. Thus, there exists a need for the continued development of improved design and analysis tools, and the development/utilization of flightworthy transparencies having the necessary birdstrike capability. It is this need to which the subject program was directed.

1.2 PROGRAM OBJECTIVE

The Air Force has made a commitment to develop, demonstrate, and apply the technologies required for the design and verification of birdstrike resistant transparent crew enclosures. The primary objective of this program was to apply advanced birdstrike technology in the analytical and technical support of ongoing AFFDL transparency efforts to improve birdstrike resistance and lower cost-of-ownership for F/RF-4, T-38, F-16, and F-111 aircraft transparencies. Support objectives were test standardization, development of a birdstrike resistance data base for existing and proposed transparency system configurations, and prediction of aircraft loss probability due to birdstrikes. A further objective was to develop and apply specific support technologies which can supply valuable information as a part of the transparency design/analysis/test cycle.

SECTION 2
COMPILATION OF ABSTRACTS (BIBLIOGRAPHY)

Presented below, in chronological order, is a compilation of abstracts taken from the referenced reports which were prepared and issued to document the work accomplished under Contract No. F33615-80-C-3401. Included also is a list of directly related papers which were presented throughout the contract period.

2.1 REPORT ABSTRACTS

2.1.1 AFWAL Reports

Blaine S. West and Kenneth I. Clayton, Alternate T-38 Transparency Development, Part I, Initial Analysis and Design, AFWAL-TR-80-3132, Part I, November 1980.

ABSTRACT: T-38 missions at speeds above the existing crew enclosure damage threshold will result in flight safety risk to aircraft and crew. This report documents the design development of alternate T-38 transparencies having the capability of defeating the impact of a four pound bird at aircraft speeds up to 400 knots. To accomplish the desired windshield/canopy redesign, a feasibility study was conducted, damage probability was determined, the birdstrike capability of existing transparencies was experimentally evaluated, edge attachment screening specimens were laboratory tested, and finite element analyses were made. Major findings from each task have been integrated into the detail design of a birdstrike resistant forward windshield panel, recommended for full-scale hardware fabrication, testing, and evaluation. Forward canopy and instructor windshield concepts are also discussed.

Blaine S. West, Alternate T-38 Transparency Development, Volume II: Baseline Birdstrike Testing, AFWAL-TR-80-3132, Part II, December 1980.

ABSTRACT: T-38 missions at speeds above the existing crew enclosure damage threshold will result in flight safety risk to aircraft. This report documents the results of a full-scale flight test program to establish the bird impact resistance of existing T-38 forward transparencies. The failure threshold for the forward windshield and forward canopy for a four-pound birdstrike at six impact locations was established. Test results are reported and discussed in detail.

Andrew J. Piekutowski, Measurement of Out-of-Plane Displacements (User's Manual for UDRI Moire Fringe Device), AFWAL-TR-81-3006, March 1981.

ABSTRACT: Instructions for use of t[illegible]RI moire fringe device are provided in this rep[illegible]t. Detailed instructions for analysis of the moire fringe patterns produced by the device are also presented. A listing of statements in a computer program named PANDIS is given. This program, written in the BASIC language is used to reduce data obtained during analysis of the fringe patterns to out-of-plane displacement data. A test problem, including sample data and output, is also presented.

Blaine S. West, Kenneth I. Clayton, and F. Joseph Giessler, Survey of Developmental Testing and In-Service Durability of F-15, F-16, and F-111 Transparencies, AFWAL-TR-81-3151, January 1982.

ABSTRACT: The objective of this program was to review the developmental test methods and operational usage history applicable to the transparencies of the F-15, F-16, and F-111 aircraft which represent monolithic stretched acrylic, monolithic coated polycarbonate, and laminated acrylic/polycarbonate state-of-the-art transparencies. Test history and operational history was obtained from a literature review and by visiting the various aircraft manufacturers, transparency vendors, and using organizations. The information obtained was analyzed to identify areas of concern which are related to manufacturing and usage problems. These areas are discussed in detail and recommendations are made for investigations which would lead to better design information, better testing procedures, and more durable transparencies.

Gregory J. Stenger, F-16 Laminated Canopy Interlayer Characterization, AFWAL-TR-82-3107, December 1982.

ABSTRACT: Laminated canopies are being fitted to F-16 aircraft in increasing numbers. The interlaminar strength of these canopies is critical to their durability and impact resistance. This report documents the tensile and shear strength of bird impact tested F-16 canopies and investigates relationships between the results of the bird impact tests and interlaminar strength of the material.

Michael P. Bouchard, Effects of Surface Flaws on Impact Resistance of Uncoated Polycarbonate, AFWAL-TR-84-3016, March 1984.

ABSTRACT: Uncoated aircraft transparency polycarbonate is highly susceptible to surface abrasions. This report describes an experimental effort of limited scope to determine the effects of flaws on the resistance of polycarbonate to the impulsed, high energy loading conditions of bird impact. Test fixturing for flaw formation and high rate load application to polycarbonate beam specimens is described. It is demonstrated that polycarbonate is sensitive to changes in scratch profile and is less sensitive to changes in scratch depth. Net absorbed energy decreases with increased scratch depth. However, scratches of any depth produce fracture if the scratch has a sharp, "V"-shaped profile.

Gregory J. Stenger, Alternate T-38 Transparency Development, Part III, Instructor's Windshield, AFWAL-TR-80-3132, Part III, January 1983.

ABSTRACT: The development of a bird impact resistant T-38 instructor's windshield resulted from recent low level mission usage which significantly increases the danger of sustaining a bird impact and has caused concern within the Air Training command (ATC) over pilot safety and aircraft survivability. The program has established the existing capability of in-service T-38 instructor's windshields and the maximum capability of the modified instructor's windshield frame and support structure which is based on the production hardware. The modification should provide a minimum capability of a four pound bird at 250 knots; twice the velocity (four times the energy) of the existing capability. This report summarizes the development of the modification, highlighting the design philosophy adopted as a result of the need to balance conflicting and restrictive design requirements.

B. Basava Raju, Blaine S. West, and Andrew J. Piekutowski, Strains from Projection Moire Data, AFWAL-TR-83-3020, February 1983.

ABSTRACT: The main objective of this program was to determine and evaluate the surface strains from out-of-plane deformations determined by the projection moire method of large surfaces experiencing static loads. The program consisted of three primary tasks: (1) design of an experiment consisting of a four-point bending fixture and a 26x6x1/4 inch flat test specimen, moire device, strain gage instrumentation, and dial gages, and the collection of experimental data for various static loads; (2) analytical prediction of the deflections and strains by small and large deflection beam theories and small deflection plate theory; (3) computation of strains from the moire deflections by a number of numerical curve fitting techniques; and (4) comparison of the strains determined from the moire technique with experimental and theoretical strains.

Tests were conducted at loads from 50 to 300 pounds in 50 pound load increments and strains were computed from moire deflections by using second and third order polynomials and a second order Legendre polynomial. both the deflections and strains were accurately determined for the flat surfaces investigated. It is recommended that the investigations be extended to evaluate the accuracy of the method for curved surfaces under dynamic response conditions.

Richard A. Nash and Blaine S. West, Alternate T-38 Transparency Development, Part IV, Parametric Studies, AFWAL-TR-80-3132, Part IV, June 1983.

ABSTRACT: Studies conducted to examine the effect of structural parameter variations on the nonlinear, dynamic response of the T-38 student windshield/support structure system to bird impact are described. The studies were conducted using the Materially And Geometrically Nonlinear Analysis (MAGNA) finite element computer program. Both static and transient dynamic analyses were conducted, examining the effects of changes to the transparency and support structure stiffness, intensity of the applied load both coupled and uncoupled, and duration of the impact event. Significant results of the finite element analysis include transparency deflection, peak load versus transparency stiffness, and resultant force plots both along the aft arch and around the impact area. A discussion of application of the finite element method to the birdstrike problem is also presented.

Gregory J. Stenger, Structural Evaluation of a Transparency with Metallic Film Interlayer, AFWAL-TR-83-3063, June 1983.

ABSTRACT: ADBIRT transparencies containing an interlaminar metallic coating have experienced some delamination in service. This report documents and compares the interlaminar material properties (tensile, shear, and peel strengths) of four different windshields. The approximate chemical composition of the metallic coated system is also documented in this report.

Kenneth I. Clayton, Gregory J. Stenger, Blaine S. West, and Paul E. Johnson, Development of an Impact Resistant Test Method for Polycarbonate, AFWAL-TR-83-3128, February 1983.

ABSTRACT: Polycarbonate offers many advantages as a structural transparency material, having excellent impact resistance as well as acceptable optical and thermal properties; however, one of the difficulties in evaluating impact resistance of polycarbonate is the lack of a universally accepted and standardized test method. Some transparency vendors rely on the falling weight impact test which yields good qualitative results. However, to date these falling weight impact tests have been performed under loosely controlled conditions, not governed by well-defined test procedures. The notched Izod test has been and continues to be used for qualitatively evaluating impact resistance of polycarbonate per MIL-P-83310, even though it has not been clearly established that this is the best method for evaluating the impact resistance of notch-sensitive polycarbonate. This report discusses six test methods and compares results from each test.

Gregory J. Stenger and Michael P. Bouchard, Environmental Effects on the Structural Properties of an Aircraft Windshield Material Having a Metallic Film Interlayer, AFWAL-TR-84-3010, March 1984.

ABSTRACT: Bird resistant transparencies containing an interlaminar metallic coating have experienced some delamination in service. This report documents and compares the interlaminar lap shear strength of baseline transparency material from two different vendors, both with and without laboratory thermal/humidity conditioning. Chemical analyses of the failure surfaces from lap shear testing are also documented.

B. Basava Raju, A Review Study of Nondestructive Test Techniques for Residual Stresses in Aircraft Transparencies, AFWAL-TR-83-3108, January 1984.

ABSTRACT: The main objectives of this program are to (1) conduct review studies on candidate nondestructive test techniques for determining residual stresses in aircraft transparencies; and (2) identify and recommend nondestructive test techniques having potential for further laboratory development and field use. The program consisted of three primary tasks: (1) a comprehensive general literature review of over 150 publications on holography, x-rays, moire, scattered-light, thermal methods, ultrasonic techniques, acoustic emission, magneto-photoelasticity, integrated photoelasticity, laser diffraction, and eddy current technique; (2) a detailed literature review on scattered light photoelasticity, ultrasonic technique I based on the Rayleigh surface waves, ultrasonic technique II based on the ultrasonic energy reflection at a liquid-solid interface, magneto-photoelasticity, and laser diffraction; (3) detailed review studies on scattered-light techniques and ultrasonic techniques I and II.

The studies revealed that the basic principles and experimental procedure of ultrasonic technique I based on Rayleigh surface waves is fairly well developed. The experimental hardware is simple, cheap, commercially available, and can readily be

employed for field measurements. The scattered-light technique is one of the well developed methods available to a stress analyst. Besides residual stresses, it has other capabilities such as dynamic, static, thermal, and elasto-plastic stress determination. Very sophisticated experimental hardware is commercially available. At present this technique is more suitable as a laboratory tool as it needs the expertise of a well trained engineer; however, the possibilities of its use in the field environment exist. Ultrasonic technique II, based on energy reflection at a liquid-solid interface, magneto-photoelasticity, and laser diffraction all need further development.

It is recommended that: (1) ultrasonic technique I, based on Rayleigh surface waves, be evaluated for use on aircraft transparency plastic materials such as polycarbonates and acrylics and be further considered for development as a field tool to nondestructively determine the residual stresses in aircraft transparencies in their installed condition; (2) scattered-light techniques be demonstrated as a nondestructive technique for quantifying residual stresses in aircraft transparencies in the laboratory and that the experimental hardware required for field use be defined and, if practical, developed.

Gregory J. Stenger, Blaine S. West, Richard A. Nash, and John P. Ryan, Definition and Reduction of the F/RF-4 Windshield Birdstrike Hazard, AFWAL-TR-84-3003, May 1984.

ABSTRACT: Birdstrikes to the crew enclosure of the USAF F-4 aircraft have resulted in major aircraft

damage coupled with severe/fatal pilot injuries. This program was initiated to develop a transparency system for the F-4 aircraft with four-pound, 500 knot capability. The seven-part study was comprised of the following: (1) identification of the design requirements, goals, and alternatives; (2) establishing the existing capability with baseline birdstrike tests; (3) evaluating various transparency designs and cross-sections; (4) assessment of the birdstrike risk; (5) evaluation of various transparency/support structure interface designs; (6) further evaluation of various designs with a parametric analysis; and (7) summarization of cost of the various alternatives. The UDRI, working closely with Goodyear Aerospace Corporation, integrated these findings into a design recommendation.

Michael P. Bouchard, Evaluation of the Effect of Simulated and Natural Environmental Exposures on Laminated F-16 Transparency Material, AFWAL-TR-84-3022, April 1984.

ABSTRACT: This investigation was carried out to determine the effects of natural and accelerated weathering on baseline laminated F-16 transparency material. Accelerated weathering consisted of ultraviolet radiation/elevated temperature, elevated temperature with alternating ultraviolet radiation/condensation, and intense sunshine with water spray. Outdoor natural weathering was accomplished in a variety of climates. Haze and transmittance tests, modified crazing tests, and flatwise tension tests were conducted to determine the effects of the exposures and to correlate natural and accelerated weathering effects.

2.1.2 UDRI Reports

Gregory J. Stenger, Measurement of Ultraviolet Radiation Intensity in the F-16 Canopy Environmental Facility, UDR-TM-81-33, October 1981.

ABSTRACT: Radiometer measurements were made in the F-16 Canopy Environmental Facility to determine the actual irradiance on the transparency surface so this facility can be compared directly with other exposure facilities as well as to establish a data base so a determination of the decrease in irradiance with time can be made. The radiation measurements were made with an International Light IL700-A Research Radiometer and photodetector with five narrow band filters (wavelengths of 297, 313, 350, 365, and 400 nanometers). Measurements were taken on new bulbs (zero hour use) and at 13 locations in the facility after the 1000 hour burn in.

Richard A. Nash, Alternate T-38 Transparency Development, Part V, Parametric Study Data, UDR-TR-82-37, March 1982.

ABSTRACT: The contents of this report consist of graphical data submitted in support of the Alternate T-38 Transparency Development, Part IV, Parametric Studies. Resultant force plots are provided for both the static and transient dynamic analyses. Deflection plots are also provided for the transient dynamic analysis.

Gregory J. Stenger, Evaluation for Polycarbonate Embrittlement in Full Scale F-16 Laminated Canopies, UDR-TM-82-28, October 1982.

Two full scale F-16 canopies were evaluated with the falling weight test method, ASTM F736-81, to determine the condition of the structural polycarbonate ply. The two three-ply canopies consisted of an acrylic outer ply, a silicon interlayer, and a polycarbonate structural ply with an interior coating. A total of 42 specimens were fabricated from three locations on each of the two canopies; canopy "A"having failed the birdstrike test, canopy "B" having passed the birdstrike test. The falling weight tests indicated no embrittlement (loss of ductility) of the polycarbonate ply.

2.2 SELECTED PAPERS/PRESENTATIONS

Bouchard, M. P., "Effects of Surface Flaws on Uncoated Polycarbonate," paper presented at the AIAA 8th Minisymposium on Aerospace Science and Technology, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, March 23, 1982.

Bouchard, Michael P., "A Modified Chemical-Stress Crazing Test Method," paper presented at the AIAA 9th Minisymposium on Aerospace Science and Technology, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, March 22, 1983.

Clayton, K. I., "Evaluation of Test Methods for Determining the Impact Resistance of Polycarbonate," paper presented at the Conference on Aerospace Transparencies, London, England, September 8-10, 1980.

Clayton, K. I., B. S. West, and Saeger, W. W., Jr. (Capt)., "Alternate T-38 Transparency Development," paper presented at the 14th Conference on Aerospace Transparent Materials and Enclosures, Scottdale, Arizona, 11-14 July 1983.

Nash, R. A., "Nonlinear Finite Element Analysis--Applications," paper presented at the 8th AIAA Minisymposium on Aerospace Science and Technology, Wright-Patterson Air Force Base, Ohio, March 23, 1982.

Nash, R. A., "Parametric Studies of the T-38 Student Windshield Using Finite Element Code MAGNA," paper presented at the Conference on Aerospace Transparent Materials and Enclosures, Scottdale, Arizona, 11-14 July 1983.

Piekutowski, Andrew J., "A Moire Technique Used to Determine Dynamic Displacements of Large Surfaces," paper presented at the Fourth SESA International Congress, Boston, Massachusetts, May 1980.

Raju, B. Basava, "Strains from Projection Moire Data," paper presented at the 8th AIAA Minisymposium on Aerospace Science and Technology, Wright-Patterson Air Force Base, Ohio, March 23, 1982.

Raju, B. Basava, B. S. West, and A. Piekutowski, "Deflections and Strains in Flat Plate Structure using Projection Moire Method," paper presented at the SESA Annual Spring Conference, Cleveland, Ohio, May 1983; also to be published in Experimental Mechanics Journal, 1984.

Simmons, Lt. R. and G. J. Stenger, "F/RF-4 Transparency Baseline Bird Impact Test Program," paper presented at the 9th AIAA Minisymposium on Aerospace Science and Technology, Wright-Patterson Air Force Base, Ohio, March 22, 1983.

Stenger, G. J., "Torsional Shear Test on Layered Material with Application to Laminated Aircraft Transparencies," paper presented at the AIAA Minisymposium on Aerospace

Science and Technology, Wright-Patterson Air Force Base, Ohio, March 25, 1981.

Stenger, G. J., "Development of Bird Impact Resistant T-38 Instructor's Windshield," paper presented at 8th AIAA Minisymposium on Aerospace Science and Technology, Wright-Patterson Air Force Base, Ohio, March 23, 1982.

Stenger, G. J., "Development of a Bird Impact Resistant T-38 Instructor's Windshield," paper presented at the SESA Annual Spring Conference, Cleveland, Ohio, May 1983.

Stenger, G. J., "Development of Bird Impact Resistant Aircraft Transparencies," presentation at UDRI Natural Environment Wind/Rain Tunnel Dedication Ceremonies, Dayton, Ohio, May 18, 1983.

Stenger, G. J. and Lt. R. Simmons, "Bird Impact Evaluation of F/RF-4 Transparency System," paper presented at the 14th Conference on Aerospace Transparent materials and Enclosures, Scottdale, Arizona, 11-14 July 1983.

West, Blaine S., "The Role of Finite Element Analysis in the Design of Birdstrike Resistant Transparencies," paper presented at the Conference on Aerospace Transparencies, Royal Aeronautical Society, London, 9 September 1980.

West, Blaine S., "Measuring the Impact Resistance of Monolithic Polycarbonate Sheet by Means of a Falling Weight," paper presented at ASTM Technical Seminar, Salt Lake City, Utah, February 20, 1981.

SECTION 3
PROGRAM ACCOMPLISHMENTS

Contributions to the technical knowledge associated with the design of birdstrike crew enclosures fall into two categories: general and specific. Some of the generic contributions resulting from this contractual effort are:

- the identification of technology deficiencies;
- the transfer of new technology to industry;
- technology demonstration through application; and
- standardization and development of test methods through participation in ASTM F7.08.

Itemized below are some specific accomplishments resulting from the program effort which was conducted under Contract No. F33615-80-C-3401 during the period February 1980 through December 1983. Details of these accomplishments are documented in the AFWAL reports referred to in Section 2.

- Assessed the birdstrike risk and established the bird impact resistance of existing T-38 forward transparencies (windshield/canopy) and instructor's windshield;

- Developed a preliminary design configuration of a forward windshield panel, along with forward canopy and instructor windshield concepts, for alternate T-38 transparencies having birdstrike resistant capability;

- Conducted analyses to examine the effect of structural parameter variations on the bird impact response of T-38 student windshield/support structure system using the materially and geometrically nonlinear analysis finite element computer program MAGNA,

- Determined and evaluated surface strains and documented instructions for using a moire fringe device and reducing resultant out-of-plane displacement data;

- Surveyed and analyzed the developmental test methods, manufacturing, and operational usage of F-15, F-16, and F-111 transparencies in order to recommend procedures needed to obtain more durable transparencies in the future;

- Developed special test methods and specimen geometries for evaluating critical transparency failure modes;

- Characterized and correlated the interlaminar strength of laminated F-16 canopies with bird impact test results;

- Compared the interlaminar metallic coating behavior of F-111 ADBIRT windshields;

- Standardized a falling weight test method for evaluating the impact resistance of polycarbonate;

- Evaluated the sensitivity of surface scratch profile/depth on the impact resistance of uncoated polycarbonate;

- Reviewed, identified, and recommended nondestructive test techniques having the potential to determine residual stresses in aircraft transparencies in the installed condition;

- Assessed the birdstrike risk and established the bird impact resistance of existing F-4 windshield and forward canopy;

- Recommended designs for developing a transparency system for the F-4 having four-pound, 500-knot capability;

- Initiated the correlation of natural versus accelerated weathering effects on F-16 laminated transparency material;

- Evaluated the analytical application of the laminated shell element in the nonlinear impact response of F-16 laminated canopies;

- Defined the requirements, designed, and fabricated a facility for simulating the flightline environmental exposure of a full scale canopy; and

- In conjunction with AFWAL/FIER, identified the major technology deficiencies associated with application of MAGNA to be, (1) a coupled bird load model, (2) the availability of adequate material properties data, and (3) the limitation on computer resources at the ASD computer facility.

SECTION 4
RECOMMENDATIONS

Recommendations for addressing existing transparency system technology deficiencies and future aircraft requirements are enumerated below.

- Develop high temperature transparency materials for advanced tactical fighter systems.
- Develop/demonstrate technology for transparency residual stress evaluation.
- Continue transparency test criteria development/ verification.
- Improve mechanical property characterization of transparency materials at both high and low strain rates.
- Continue development/evaluation of new materials and material systems for transparency and support structure.
- Validate/demonstrate coupled bird load model.
- Continue to expand the existing data base and establish a more detailed data base on in-service problems, failure modes, and cause for removal.
- Correlate laboratory aged transparency test results with in-service aged transparencies.
- Develop battle damage repair techniques for transparencies.
- Develop transparency criteria/methodology for defeating hostile environment.
- Further develop/demonstrate in-flight/flightline environmental simulator.

- Update AFWAL-TR-80-3003, "Guidelines for the Design of Aircraft Windshield/Canopy systems," as required.
- Continue to validate/demonstrate new technology through application to existing and new aircraft systems.
- Enhance analysis capabilities through access to increased computer resources.

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