FAA DEVELOPMENT OF RELIABLE MODELING METHODOLOGIES FOR FAN BLADE OUT CONTAINMENT ANALYSIS
Part 2: BALLISTIC IMPACT TESTING

This report summarizes the ballistic impact testing that was conducted to provide validation data for the development of numerical models of blade out events in fabric containment systems. The ballistic impact response of two different fiber materials - Kevlar 49 (E.I. DuPont Nemours and Company) and Zylon AS (Toyobo Co., Ltd.) was studied by firing metal projectiles into dry woven fabric specimens using a gas gun. The shape, mass, orientation and velocity of the projectile were varied and recorded. In most cases the tests were designed such that the projectile would perforate the specimen, allowing measurement of the energy absorbed by the fabric. The results for both Zylon and Kevlar presented here represent a useful set of data for the purposes of establishing and validating numerical models for predicting the response of fabrics under conditions simulating those of a jet engine blade release situations. In addition some useful empirical observations were made regarding the effects of projectile orientation and the relative performance of the different materials.
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LIST OF ACRONYMS

FAA  Federal Aviation Administration
NASA  National Aeronautics and Space Administration

Note: Acronyms should be defined at the first occurrence in the text only if the acronym is subsequently used within the report. If it is not used more than once, then the acronym should be spelled out (for example, if the acronym FAA is used only once, then use Federal Aviation Administration).

All acronyms are required to be defined in the abstract, executive summary, body of the report, conclusions, and in each appendix.
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## APPENDICES

A – PROCEDURE FOR COMPUTING EULER ANGLES  
B – SIMPLE TEST RESULTS: EVALUATING NASA’S ZYLON AS 1500D FABRIC
EXECUTIVE SUMMARY

A team consisting of Arizona State University, Honeywell Engines & Systems, NASA Glenn Research Center and SRI International collaborated to develop computational models and verification testing for designing and evaluating turbine engine fan blade fabric containment structures. This research was conducted under the Federal Aviation Administration’s Airworthiness Assurance Center of Excellence and sponsored by the Aircraft Catastrophic Failure Prevention Program. The research was directed towards improving the modeling of a turbine engine fabric containment structure for an engine blade-out containment demonstration test required for certification of aircraft engines.

In the first phase of this research work [1,2,3,4], much progress was made in testing and computational analysis. A fabric material model was developed for Kevlar and Zylon fabrics. Static testing of containment wraps subjected to loads through a blunt nose impactor was carried out at ASU. Ballistic testing of containment wraps subjected to a high velocity blunt projectile was carried out at NASA-Glenn. These tests have provided test cases (benchmark results) to validate the developed finite element methodology. While the work performed in the previous research program met the stated objectives, improvements in robustness and confidence of the finite element simulations and predictions was desired.

The research conducted in this second phase brings a new level of capability to design and develop fan blade containment systems for turbine engines. To achieve the program objectives, a plan consisting of four technical tasks was developed and implemented as follows:

Task 1: Robust FE Model Development-The objective of this task was to increase confidence and robustness in the material models for the Kevlar and Zylon material models developed in phase 1.

Task 2: Improve FE Modeling Capability for Multiple Layers of Fabric-In Phase I program, most of the LS-DYNA models used a single element through the thickness to model the fabric, which ranged from one to twenty four layers.

Task 3: 1500 denier (d) Zylon® Material Model Development-In the previous program, limited ballistic and static tests of 1500d Zylon indicated this configuration of Zylon might have the potential to offer a 60 percent weight advantage over a similar configuration of Kevlar 49 fabric for the same fragment energy. The objective of this task was to develop and validate a material model for 1500 Denier Zylon. It should be noted that during the conduct of this study, it was discovered that Zylon was found have excessive deterioration due to heat and humidity. As a result of this, it was decided that the remainder of this study would focus only on Kevlar fabrics.

Task 4: Engine Simulations-As in the previous program, the objective of this task was to validate improvements to the material models and FE methods developed under this program as they relate to propulsion engine fan blade containment. Existing fabric material models and modeling methods and improvements to the material models and methods were validated using fan containment test data.
Each member of the team took a leadership role and developed a comprehensive report describing the details of the research task and the findings. The comprehensive report is made up of four report parts. These reports are as follows:

1) Arizona State University Department of Civil Engineering, Part 1: Fabric Material Tests
2) NASA-Glenn Research Center, Part 2: Ballistic Testing
3) SRI International, Part 3: Material Model Development and Simulation of Experiments

This report contains a description of and results from Part 2 of this project, the ballistic impact testing conducted at NASA Glenn Research Center.
1. INTRODUCTION

In the last thirty years the use of aramid fabrics in jet engine blade containment systems has become common. It is recognized that high strength and high elongation fabrics, combined with innovative structural concepts can provide a light weight, effective fan case system that provides the strength required to safely handle impact loads, blade rub loads and the large dynamic loads caused by rotor imbalance. Aramid and other high strength fibers and fabrics have been studied extensively due to their application in a wide range of products such as bullet-proof vests, cut-resistant gloves, tires and sports equipment. However, relatively small amounts of data exist in the public domain for the impact response of fabrics in configurations that are similar to those used in jet engine applications.

Containment design is currently largely based on empirical methods but there is strong motivation on the part of jet engine manufacturers to develop numerical models that can be used to help in the design process of fan containment systems, thereby reducing the cost of testing and increasing confidence and reliability in the design. A number of research and commercial computer programs are available that can simulate the impact of a released fan blade on the case (a blade-out event). These are generally transient, explicit integration finite element codes [5, 6]. The codes themselves are accurate and have been validated by years of use but the constitutive, failure and contact models are still the subjects of active research. A large body of data and research studies exist with regard to high strain rate behavior and impact response and constitutive and failure models for metals [7, 8, 9]. While there is data available in the literature on the impact response of fabrics [10, 11, 12], and models have been developed to simulate fabric impact response [13, 14, 15] the body of literature is much smaller than for metals. In addition, studies tend to focus on applications other than jet engines (such as body armor) and generally consider impacts by small high velocity projectiles. Jet engine fan containment impact involves a larger projectile at sub-sonic velocities.

To address the lack of data and to improve the material models in the range of jet engine applications, the Federal Aviation Administration (FAA) recently completed a project aimed at developing improved computational tools for designing fabric-based engine containment systems [1, 2, 3, and 4]. This study was done on Kevlar 49® and Zylon® as spun (AS) fabric and involved static testing and modeling, conducted by The Arizona State University, ballistic impact testing of fabric rings, conducted by the NASA Glenn Research Center, material model development and simulation of experiments, conducted by SRI International and model simulations of ballistic tests, fan blade-out and generic engine modeling conducted by Honeywell Engines Systems and Services.

As a follow-up to that work, a second phase was conducted with the objective of increasing the confidence and robustness of the material models. This involved additional finite element model development and additional static and ballistic impact testing. This report summarizes the ballistic impact testing that was conducted to provide validation data for the numerical model development. In addition some useful empirical
observations were made regarding the effects of projectile orientation and the relative performance of the different materials.

2. METHODS

The ballistic impact response of fabrics was studied by firing metal projectiles into dry woven fabric specimens using a gas gun. The shape, mass, orientation and velocity of the projectile were varied and recorded. In most cases the tests were designed such that the projectile would perforate the specimen, allowing measurement of the energy absorbed by the fabric.

2.1 MATERIALS

Fabrics woven from two different fiber materials - Kevlar 49 (E.I. DuPont Nemours and Company) and Zylon AS (Toyobo Co., Ltd.) - were tested. Kevlar is an aramid material with a long history in impact applications in general and fan containment systems in particular [16, 17]. Zylon has been under development more recently. A number of studies have demonstrated that, when stored and tested under laboratory conditions, Zylon demonstrates superior performance over Kevlar [18, 19]. This study considered a single fabric architecture for Kevlar and two architectures for Zylon. The fibers and architecture were selected so that two materials of similar architecture were compared, and two different architectures of the same material (Zylon) were compared. The fiber and weave parameters of the materials tested are shown in Table 1 [14].

2.2 TEST CONFIGURATION

The test specimens consisted of layers of 0/90 plain woven cloth, 25 cm (10 in) wide, wrapped around a ring shaped fixture as shown in Figure 1. The fixture was steel and had an outer diameter of 102 cm (40 in), a thickness of 2.5 cm (1 in) and a height the same as the fabric width (25 cm). The fabric was rolled around the fixture under a controlled tension of 25 N (5.5 lb) to make up the desired number of layers. The fixture had a 25.4 cm (10 in) circumferential gap at the impact location. It was placed in front of the gun barrel at an incline of 15° so that the projectile, after exiting the gun barrel, passed over the front edge of the ring, passed through the gap in the ring fixture and impacted the fabric from the general direction of the center of the ring. Because of the circumferential gap, and the tension on the specimen, the fabric was flat at the region where impact occurred, rather than following the curved shape of the ring fixture. This configuration was chosen rather than a flat specimen held in a square or
Figure 1. Fabric Specimen Wrapped Around Ring Fixture. Arrow Shows the Location of Impact.

Table 1. Fabric Properties

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<tr>
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</table>
rectangular fixture because experience has shown that in this latter configuration the boundary conditions play a major role in the response of the fabric specimen.

Three different projectiles were used in this study. The first was a rectangular shaped, 304L stainless steel article, 10.2 cm (4 in) long, 5.1 cm (2 in) high and 0.8 cm (5/16 in) thick (Figure 2), with a nominal mass of 320 gm. The front edge and the corners of the projectile were machined with a full radius. This projectile was designated Projectile A. This is the same projectile as was used in Phase I of this program [2]. The second projectile was also 304L stainless steel, but had a length of 17.8 cm (7 in), a height of 3.8 cm (1.5 in), a thickness of 0.60 cm (.235 in) and the same nominal mass as Projectile A. The front edge and corners also were machined with a full radius (Figure 2). The second projectile was designated Projectile B. The third projectile which was used in only two tests was the same as projectile A, but measured 6 inches in length instead of 4 inches. The third projectile was designated Projectile C.

The gas gun used to accelerate the projectile consisted of a pressure vessel with a volume of 0.35 m$^3$ (12.5 ft$^3$), a gun barrel with a length of 12.2 m (40 ft) and an inner diameter of 20.32 cm (8 in). A photograph of the gun is shown in Figure 3. The pressure vessel and the gun barrel were mated by a flange on each side with a number of layers of Mylar® sheet sandwiched between the flanges to seal the pressure vessel and act as a burst valve. Helium gas was used as the propellant. The pressurized helium was released into the gun barrel by applying a voltage across a Nichrome wire embedded in the Mylar sheets, causing the Mylar sheets to rupture. The projectile was supported inside an aluminum can-shaped cylindrical sabot that was machined to fit snugly inside the gun barrel. The orientation of the projectile was controlled by supporting the projectile either with rigid foam or with an aluminum wedge welded to the bottom of the sabot. The sabot was stopped at the end of the gun barrel by a thick steel plate with a rectangular slot large enough to allow the projectile to pass through. The gun barrel was evacuated to reduce blast loading on the specimen and to reduce the amount of pressure required to achieve the desired impact velocity.
A number of different high-speed digital video cameras were used to obtain both qualitative and quantitative information from each test. Figure 4 shows sequences of still images obtained from two Phantom 7 cameras (Vision Research, Inc.). The impact velocity and exit velocity were measured using the digital video cameras. The orientation of the projectile was measured from the location of three points on the projectile that defined a local moving coordinate system and three points at a fixed location in the background that defined a laboratory coordinate system. The laboratory coordinate system consisted of the X axis in the direction of the gun axis, a Z axis in the vertical upward direction and a Y axis defined by the vector product of Z and X. The orientation of the projectile was defined by a set of three Euler angles defined by a rotation $\theta$ (roll), about the laboratory X axis, followed by a rotation $\psi$ (pitch) about the rotated y-axis, followed by a rotation $\phi$ (yaw) about the (twice) rotated z-axis. The coordinate systems are shown in Figure 5. The positions of the points that defined the coordinate systems were measured using a stereo imaging system (PONTOS, GOM mbH) coupled with a pair of calibrated Phantom 5 high-speed digital video cameras (Vision Research, Inc). The Euler angles were computed by defining the unit vectors in each of the two coordinate systems, forming the direction cosine matrix and equating the direction cosine matrix to the coordinate transformation matrix (Appendix A).
2.3 TEST MATRIX

Three sets of tests were conducted in this program. The first set consisted of tests in which the orientation and aspect ratio of the projectile were varied from those conducted in the Phase I program [2]. In the second set of tests additional data were taken on 1500 denier Zylon in the same test configuration as the Phase I program. A final set of two tests was conducted on a fabric ring in which there was essentially no tension on the fabric.

Figure 4. Three Still images from typical tests. Top and Side Views.
3. RESULTS

A total of 46 successful impact tests were conducted. A test was considered successful if the velocity before and after impact and the orientation at the impact point could be accurately measured. Results for the first set of tests, in which the projectile orientation and aspect ratio were varied, are shown in Table 2. It was not possible to control the orientation of the projectile such that it exactly matched the desired orientation, and in some cases there was considerable deviation.

The amount of energy absorbed by the fabric was highly dependent on the orientation of the projectile at impact. While no correlation was found between the roll angle and the energy absorbed, there was a dependency on both pitch and yaw angles. Figure 6 shows the energy absorbed, normalized by the overall fabric specimen areal weight, as a function of the absolute value of the projectile yaw angle for the tests shown in Table 2. It can be observed that the absorbed energy to increases as the absolute value of the yaw angle increases. The figure shows that the Zylon material absorbs more energy overall, and that as the yaw angle increases the effectiveness of the 500 denier Zylon approaches that of the 1500 denier Zylon. It may be hypothesized that as the yaw angle increases and the projectile appears less sharp, the energy absorption is less localized and the architecture of the fabric plays a less important role.

The yaw angle of the projectile has the biggest effect of the three angles on the projected area of the projectile on the fabric. The projected area of the projectile can be computed
Table 2 Results from Impact Tests with Varying Projectile Orientation and Aspect Ratio
from the planar area of the projectile multiplied by the scalar product of the unit vectors normal to the projectile and normal to the fabric. That is,

\[ A_p = A(\vec{e}_2 \cdot \vec{t}_n) \]  

(1)

Where \( A_p \) is the projected area of the projectile, \( A \) is the planar area of the projectile, \( \vec{e}_2 \) is the unit normal vector to the projectile (Figure 5) and \( \vec{t}_n \) is the unit normal to the fabric specimen at the impact point. In this case, \( \vec{t}_n = \vec{I}_1 \cos(15) + \vec{I}_3 \sin(15) \) where \( \vec{I}_1 \) and \( \vec{I}_3 \) are shown in Figure 5.

![Diagram](image-url)

Figure 6. Normalized Absorbed Energy as a Function of the Projectile Yaw Angle

The effect of the projectile projected area on the energy absorbed, normalized by the total areal weight of the fabric specimen, is shown in Figure 7 for the Kevlar and 1500 denier Zylon. While there is some scatter in the results, there appears to be a linear relationship between the normalized energy absorbed and the projected area of the projectile. In addition, it appears that the actual shape of the projectile had less of an effect than the presented area itself. It can also be seen in Figure 7 that the normalized energy absorbed by Zylon is approximately twice as that by Kevlar of the same areal weight and architecture.

One of the objectives of this study was to expand upon the Phase I results for 1500 denier Zylon [2] to verify the enhanced performance over Kevlar. This involved a number of
impact tests in which the nominal orientation of the projectile was (0, 0, 0) pitch, roll and yaw (Table 3). Figure 8 shows the normalized energy for the 1500 denier Zylon from the two sets of experiments, as well as the earlier phase I results for Kevlar. The material from the present study (Phase II) did not perform as well as that from the earlier study (Phase I). However, both sets of Zylon absorbed significantly more energy than Kevlar.

![Figure 7 Normalized Absorbed Energy as a Function of the Projectile Projected Area](image)

The difference in impact strength between Phase I and Phase II for the 1500 denier Zylon was considered significant and worthy of investigation. It was hypothesized that the difference was due to the known age related degradation in the mechanical properties of the Zylon. In Phase I of this study [2] the 1500 denier Zylon was fabricated in March, 2002 and the impact testing was conducted between May 9 and May 21, 2002, a period of two to three months. In the Phase II study the material was manufactured in June, 2004 and the impact testing was conducted between July 21 and Aug. 30, 2005, over a year later. During the period between manufacture and testing in both phases the material was stored under normal indoor laboratory conditions in a closed container to prevent any light.

A test program was conducted at the ASU Department of Civil Engineering to investigate age-related changes in strength, modulus and toughness of 1500 denier Zylon stored under laboratory conditions. A summary of this study is included in Appendix B of this report. The study concluded that there is a statistically significant decrease in the strength and toughness of the fabric with age, and a small decrease in the stiffness. Over a 12 month period the strength decreased by 9% and the toughness decreased by 22%. The stiffness decreased by 2%. In addition, tests conducted on virgin fabric 8 months
after delivery to the fabric weaver showed a 40% decrease in the measured strength compared to the manufacturer’s published value. These results support the hypothesis that the reduction in the impact energy absorption capacity of the 1500 denier Zylon between Phase I and Phase II was, in fact, due to age-related changes in mechanical properties.

![Figure 8. Normalized Energy Absorbed as a Function of the Number of Fabric Layers. Results of This Study (Phase II) Compared With Those in Phase I](image)

The final set of tests was performed to look at the effect of fabric tension. In these tests eight layers of 500d Zylon were wrapped around the fixture with essentially no tension and impacted using projectile A with a desired orientation of (0, 0, 0) pitch, roll and yaw respectively. The results of these tests are shown in Table 4. The results were compared with the 500d Zylon tests (Projectile A) from Table 2 and are shown in Figure 9. Figure 9 shows the increase in absorbed energy per unit fabric total areal weight as a function of projectile projected area for the specimens under the nominal tension. Results from the two tests at low tension show no significant difference. However, it should be noted that only two tests were conducted at low specimen tension and more tests are needed to gain more confidence in this conclusion.
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Table 3. Results of Impact Tests on 1500d Zylon

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<td>6/27/2007</td>
<td>8</td>
<td>322.73</td>
<td>-4.26</td>
<td>24.48</td>
<td>-1.861686</td>
<td>929.78</td>
<td>12959.84</td>
<td>869.3695</td>
<td>11330.47</td>
<td>1629.366</td>
<td>0.125724</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Low Tension Test Results
4. DISCUSSION AND CONCLUSIONS

The test configuration described here was designed to be somewhat representative of fabric containment systems used in jet engines, while maintaining repeatability and simplicity in the test. The results show that under the conditions of this test, Zylon is able to absorb over twice the energy than Kevlar when compared on an overall weight basis. The normalized energy absorbed is relatively insensitive to the number of layers of material. These results are consistent with results of Phase I of this study [2]. This allows for a fairly simple design procedure if the assumption is made that the amount of energy absorbed per unit weight is independent of the number of layers of material. Except in cases where the yaw angle was high, the heavier weight Zylon material performed better than the lighter material, for the same overall weight. This is consistent with the results of Phase I. The energy absorbed by the fabric when normalized by the overall areal weight of the fabric ring is approximately linearly related to the presented area of the projectile at impact and, within the parameters of this study, is independent of the actual shape of the projectile.

The data presented here were taken using Zylon that had been stored for several months under normal laboratory conditions, without exposure to extreme temperature and humidity. It has been reported widely that the performance of Zylon degrades significantly under certain conditions of temperature and humidity which are likely to be
encountered in many applications. However these results indicate that degradation in the mechanical properties of Zylon occurs even under favorable conditions. The deterioration of strength over time seen in the current Zylon fabric makes the fabric impractical for long term use in engine containment systems.

The limited testing performed under conditions of no fabric tension indicate that there is no significant difference in energy absorption between the two tested conditions. However, this should be validated by additional testing.

The results for both Zylon and Kevlar presented here represent a useful set of data for the purposes of establishing both empirical and numerical models for predicting the response of fabrics under conditions simulating those of a jet engine blade release situations.

5. REFERENCES

Appendix A. Procedure for Computing Euler Angles

Using the 3-D photogrammetry system the position of three points on the projectile and three points on a fixed background can be measured. The points on the fixed background are used to define unit orthogonal vectors \((\hat{i}_1, \hat{i}_2, \hat{i}_3)\) in the laboratory system. The points on the projectile are used to define a moving system of unit orthogonal vectors attached to the projectile. At any time, the position of the projectile can be described as a translation plus a sequence of three rotations:

1. Roll \((\theta)\) about the projectile \(x\)-axis
2. Pitch \((\psi)\) about the projectile rotated \(y\)-axis
3. Yaw \((\varphi)\) about the projectile twice-rotated \(z\)-axis

For the purposes of defining the orientation of the projectile we can ignore the translation terms. Imagine the projectile initially in a position where the projectile coordinate system lines up with the lab coordinate system. The position of a point, \(R\), on the projectile can be described by:

\[
\vec{R} = r_1\hat{i}_1 + r_2\hat{i}_2 + r_3\hat{i}_3 = r_1\hat{i}_1 + r_2\hat{i}_2 + r_3\hat{i}_3
\]  
\[\text{(A1)}\]

Where \((\hat{i}_1, \hat{i}_2, \hat{i}_3)\) are the unit vectors attached to the projectile. If the projectile is rotated by the angle \(\theta\) about the laboratory \(X\) axis, the vector \(\vec{R}\) becomes \(\vec{R}'\), given by

\[
\vec{R}' = r_1\hat{e}_1 + r_2\hat{e}_2 + r_3\hat{e}_3 = r_1\hat{i}_1 + r_2\hat{i}_2 + r_3\hat{i}_3
\]  
\[\text{(A2)}\]

The unit vectors \((\hat{e}_1, \hat{e}_2, \hat{e}_3)\) are the rotated unit vectors in the projectile \((x, y, z)\) directions. These unit vectors can be found in terms of the \((\hat{i}_1, \hat{i}_2, \hat{i}_3)\) vectors from

\[
\begin{align*}
\hat{e}_1 &= (\hat{e}_1 \cdot \hat{i}_1)\hat{i}_1 + (\hat{e}_1 \cdot \hat{i}_2)\hat{i}_2 + (\hat{e}_1 \cdot \hat{i}_3)\hat{i}_3 \\
\hat{e}_2 &= (\hat{e}_2 \cdot \hat{i}_1)\hat{i}_1 + (\hat{e}_2 \cdot \hat{i}_2)\hat{i}_2 + (\hat{e}_2 \cdot \hat{i}_3)\hat{i}_3 \\
\hat{e}_3 &= (\hat{e}_3 \cdot \hat{i}_1)\hat{i}_1 + (\hat{e}_3 \cdot \hat{i}_2)\hat{i}_2 + (\hat{e}_3 \cdot \hat{i}_3)\hat{i}_3
\end{align*}
\]  
\[\text{(A3)}\]

Inserting (A3) into (A2) and equating the vector components leads to

\[
\begin{bmatrix}
r'_1 \\
 r'_2 \\
r'_3
\end{bmatrix} =
\begin{bmatrix}
\hat{e}_1 \cdot \hat{i}_1 & \hat{e}_2 \cdot \hat{i}_1 & \hat{e}_3 \cdot \hat{i}_1 \\
\hat{e}_1 \cdot \hat{i}_2 & \hat{e}_2 \cdot \hat{i}_2 & \hat{e}_3 \cdot \hat{i}_2 \\
\hat{e}_1 \cdot \hat{i}_3 & \hat{e}_2 \cdot \hat{i}_3 & \hat{e}_3 \cdot \hat{i}_3
\end{bmatrix}
\begin{bmatrix}
r_1 \\
r_2 \\
r_3
\end{bmatrix}
\]  
\[\text{(A4)}\]

In terms of the rotation angle, \(\theta\), this is
\[
\begin{bmatrix}
   r_1' \\
r_2' \\
r_3'
\end{bmatrix} = \begin{bmatrix}
   1 & 0 & 0 \\
   0 & \cos(\theta) & -\sin(\theta) \\
   0 & \sin(\theta) & \cos(\theta)
\end{bmatrix} \begin{bmatrix}
   r_1 \\
r_2 \\
r_3
\end{bmatrix}
\]  
\ \ \ \text{(A5)}

Assume that the projectile goes through another rotation, \(\psi\), about the projectile \(y\)-axis, so that the vector \(R'\) becomes \(R''\) and the unit vectors \((\hat{e}_1, \hat{e}_2, \hat{e}_3)\) become \((\hat{f}_1, \hat{f}_2, \hat{f}_3)\). The vector \(R''\) can be written as:

\[
R'' = r_1\hat{f}_1 + r_2\hat{f}_2 + r_3\hat{f}_3 = r_1^*\hat{e}_1 + r_2^*\hat{e}_2 + r_3^*\hat{e}_3 = r_1'\hat{i}_1 + r_2'\hat{i}_2 + r_3'\hat{i}_3
\]
\ \ \ \text{(A6)}

Similar to Eqn. (A3), the components of \(\hat{f}\) can be written in terms of the components of \(\hat{e}\) as:

\[
\begin{align*}
\hat{f}_1 &= (\hat{f}_1 \cdot \hat{e}_1)\hat{e}_1 + (\hat{f}_1 \cdot \hat{e}_2)\hat{e}_2 + (\hat{f}_1 \cdot \hat{e}_3)\hat{e}_3 \\
\hat{f}_2 &= (\hat{f}_2 \cdot \hat{e}_1)\hat{e}_1 + (\hat{f}_2 \cdot \hat{e}_2)\hat{e}_2 + (\hat{f}_2 \cdot \hat{e}_3)\hat{e}_3 \\
\hat{f}_3 &= (\hat{f}_3 \cdot \hat{e}_1)\hat{e}_1 + (\hat{f}_3 \cdot \hat{e}_2)\hat{e}_2 + (\hat{f}_3 \cdot \hat{e}_3)\hat{e}_3
\end{align*}
\]
\ \ \ \text{(A7)}

The twice rotated vector \(R''\) can then be written in terms of the unit vectors \((\hat{e}_1, \hat{e}_2, \hat{e}_3)\):

\[
R'' = \left[ l_1(\hat{f}_1 \cdot \hat{e}_1) + r_2(\hat{f}_2 \cdot \hat{e}_1) + r_3(\hat{f}_3 \cdot \hat{e}_1) \right] \hat{e}_1 + \left[ l_1(\hat{f}_1 \cdot \hat{e}_2) + r_2(\hat{f}_2 \cdot \hat{e}_2) + r_3(\hat{f}_3 \cdot \hat{e}_2) \right] \hat{e}_2 + \left[ l_1(\hat{f}_1 \cdot \hat{e}_3) + r_2(\hat{f}_2 \cdot \hat{e}_3) + r_3(\hat{f}_3 \cdot \hat{e}_3) \right] \hat{e}_3
\]
\ \ \ \text{(A8)}

Equating this to the components of \(R''\) in Eqn. (A6) gives

\[
\begin{bmatrix}
   r_1' \\
r_2' \\
r_3'
\end{bmatrix} = \begin{bmatrix}
   \hat{f}_1 \cdot \hat{e}_1 & \hat{f}_2 \cdot \hat{e}_1 & \hat{f}_3 \cdot \hat{e}_1 \\
   \hat{f}_1 \cdot \hat{e}_2 & \hat{f}_2 \cdot \hat{e}_2 & \hat{f}_3 \cdot \hat{e}_2 \\
   \hat{f}_1 \cdot \hat{e}_3 & \hat{f}_2 \cdot \hat{e}_3 & \hat{f}_3 \cdot \hat{e}_3
\end{bmatrix} \begin{bmatrix}
   r_1 \\
r_2 \\
r_3
\end{bmatrix}
\]
\ \ \ \text{(A9)}

In terms of the rotation angle \(\psi\) this is:

\[
\begin{bmatrix}
   r_1' \\
r_2' \\
r_3'
\end{bmatrix} = \begin{bmatrix}
   \cos(\psi) & 0 & \sin(\psi) \\
   0 & 1 & 0 \\
   -\sin(\psi) & 0 & \cos(\psi)
\end{bmatrix} \begin{bmatrix}
   r_1 \\
r_2 \\
r_3
\end{bmatrix}
\]
\ \ \ \text{(A10)}
But the components of $\mathbf{R}''$ in the laboratory coordinate system can be given in terms of $r_1^*$, $r_2^*$ and $r_3^*$ using Eqn. (A6) and (A3):

$$\begin{bmatrix} r_1^* \\ r_2^* \\ r_3^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} r_1^* \\ r_2^* \\ r_3^* \end{bmatrix}$$  \hspace{1cm} (A11)

Substituting Eqn. (A11) into (A10) gives:

$$\begin{bmatrix} r_1^* \\ r_2^* \\ r_3^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix}$$  \hspace{1cm} (A12)

Finally, let the projectile go through a third rotation, $\phi$, about the twice rotated projectile $z$-axis, so that the vector $\mathbf{R}''$ is rotated to $\mathbf{R}'''$ given in the lab coordinate system by $\mathbf{R}''' = r_1'''\hat{i}_1 + r_2'''\hat{i}_2 + r_3'''\hat{i}_3$

Following a similar procedure that led to Eqn. (A12) leads to

$$\begin{bmatrix} r_1''' \\ r_2''' \\ r_3''' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ -\sin\psi & 0 & \cos\psi \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix}$$  \hspace{1cm} (A13)

or

$$\begin{bmatrix} r_1''' \\ r_2''' \\ r_3''' \end{bmatrix} = \begin{bmatrix} \cos\psi \cos\varphi & -\cos\psi \sin\varphi & \sin\psi \\ \cos\theta \sin\varphi + \sin\theta \sin^2\psi \cos\varphi & \cos\theta \cos\varphi - \sin\theta \sin\psi \sin\varphi & -\sin\theta \cos\psi \\ \sin\theta \sin\varphi - \cos\theta \sin\psi \cos\varphi & \sin\theta \cos\varphi + \cos\theta \sin\psi \sin\varphi & \cos\theta \cos\psi \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix}$$  \hspace{1cm} (A14)

The unit vectors defining the projectile and laboratory coordinate systems were defined using markers placed in the high speed video field of view, as shown schematically in Figure A1. The unit vectors on the projectile were defined as
\[ \hat{\mathbf{i}}_1 = (\vec{r}_b - \vec{r}_a) / |(\vec{r}_b - \vec{r}_a)| \]  
(A15)

\[ \mathbf{\tilde{i}}_2 = \frac{\left[(\vec{r}_c - \vec{r}_e) \times \hat{\mathbf{i}}_3\right]}{|(\vec{r}_c - \vec{r}_e) \times \hat{\mathbf{i}}_3|} \]  
(A16)

\[ \hat{\mathbf{i}}_3 = \hat{\mathbf{i}}_1 \times \hat{\mathbf{i}}_2 \]  
(A17)

The unit vectors in the laboratory coordinate system were defined as:

\[ \hat{\mathbf{I}}_1 = (\vec{r}_b - \vec{r}_A) / |(\vec{r}_b - \vec{r}_A)| \]  
(A18)

\[ \hat{\mathbf{I}}_3 = (\vec{r}_C - \vec{r}_d) / |(\vec{r}_C - \vec{r}_d)| \]  
(A19)

\[ \hat{\mathbf{I}}_2 = \hat{\mathbf{I}}_3 \times \hat{\mathbf{I}}_1 \]  
(A20)

Any vector, \( \vec{R} \), in the laboratory coordinate system can be obtained from the components in the blade coordinate system:

\[ \vec{R} = r_1 \hat{\mathbf{I}}_1 + r_2 \hat{\mathbf{I}}_2 + r_3 \hat{\mathbf{I}}_3 = R_1 \hat{\mathbf{I}}_1 + R_2 \hat{\mathbf{I}}_2 + R_3 \hat{\mathbf{I}}_3 \]  
(A21)

\[ \vec{R} = r_1 \left[ (\hat{\mathbf{i}}_1 \cdot \hat{\mathbf{I}}_1) \hat{\mathbf{I}}_1 + (\hat{\mathbf{i}}_2 \cdot \hat{\mathbf{I}}_2) \hat{\mathbf{I}}_2 + (\hat{\mathbf{i}}_3 \cdot \hat{\mathbf{I}}_3) \hat{\mathbf{I}}_3 \right] + r_2 \left[ (\hat{\mathbf{i}}_2 \cdot \hat{\mathbf{I}}_2) \hat{\mathbf{I}}_2 + (\hat{\mathbf{i}}_3 \cdot \hat{\mathbf{I}}_3) \hat{\mathbf{I}}_3 \right] + r_3 \left[ (\hat{\mathbf{i}}_3 \cdot \hat{\mathbf{I}}_3) \hat{\mathbf{I}}_3 + (\hat{\mathbf{i}}_1 \cdot \hat{\mathbf{I}}_1) \hat{\mathbf{I}}_1 + (\hat{\mathbf{i}}_2 \cdot \hat{\mathbf{I}}_2) \hat{\mathbf{I}}_2 \right] \]  
(A22)

and therefore

\[
\begin{align*}
\begin{bmatrix}
R_1 \\
R_2 \\
R_3
\end{bmatrix} &=
\begin{bmatrix}
\hat{i}_1 \cdot \hat{\mathbf{I}}_1 & \hat{i}_2 \cdot \hat{\mathbf{I}}_2 & \hat{i}_3 \cdot \hat{\mathbf{I}}_3 \\
\hat{i}_1 \cdot \hat{\mathbf{I}}_2 & \hat{i}_2 \cdot \hat{\mathbf{I}}_2 & \hat{i}_3 \cdot \hat{\mathbf{I}}_3 \\
\hat{i}_1 \cdot \hat{\mathbf{I}}_3 & \hat{i}_2 \cdot \hat{\mathbf{I}}_3 & \hat{i}_3 \cdot \hat{\mathbf{I}}_3
\end{bmatrix}
\begin{bmatrix}
r_1 \\
r_2 \\
r_3
\end{bmatrix}
\end{align*}
\]
(A23)

The matrix in Eqn. (23) can be easily computed and is the same as that in Eqn. (A14). Our procedure for computing the Euler angles was to compute the terms in the matrix of Eqn. (A23) from the positions of points \( a, b, c, A, B, C \), utilizing Eqns. (A15) – (A20) and then equate the terms of that matrix with those of Eqn. (A14).

For example, equating component (1, 3) in the two matrices gives

\[ \psi = \sin^{-1}(\hat{\mathbf{i}}_3 \cdot \hat{\mathbf{I}}_1) \]  
(A24)

Using this result and equating components (1, 2) gives
\[ \varphi = \sin^{-1}\left[ -\frac{(\hat{i}_2 \cdot \hat{i}_1)}{\cos(\psi)} \right] \]  

(A25)

Using components (3, 3) and Eqn. (A24) gives

\[ \theta = \cos^{-1}\left[ \frac{(\hat{i}_3 \cdot \hat{I}_3)}{\cos(\psi)} \right] \]  

(A26)

Care must be taken since the above formulas do not have unique solutions on their own. For example \( \sin(\theta) = \sin(180-\theta) \).

Figure A1. Projectile (left) and Background Coordinate Systems
Appendix B

Technical Report

Simple Tension Test Results:
Evaluating NASA’s Zylon AS 1500D Fabric

Dept. of Civil Engineering
Arizona State University
Tempe, AZ 85287

February 2006
Overview

Tension tests of the NASA Zylon 1500D fabrics were carried out to find out the fabric properties. Questions were raised about the NASA ballistic test results involving Zylon 1500D fabric from Phase I of this research. The recent Phase II NASA ballistic test results showed a decrease in energy absorption from the Phase I tests. These tension tests were conducted at Arizona State University (ASU) to try to understand the differences in the NASA test results. The basic properties of the fabric as tested are shown in Table 1.

Table 1 Specimen Properties for Zylon AS–1500D

<table>
<thead>
<tr>
<th>Yarn Count</th>
<th>Bulk Density (lb/in³)</th>
<th>Linear Density (lb/in)</th>
<th>c/s Area per Yarn (in²)</th>
<th>Specimen Size (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 x 17</td>
<td>0.00567358</td>
<td>9.13395(10⁻⁷)</td>
<td>1.61(10⁻⁴)</td>
<td>2.5 x 10.25</td>
</tr>
</tbody>
</table>

Test Results

All samples referred to in this report were manufactured by Toyobo. Warp and fill yarns were all taken from fabric weaved at Lincoln Fabrics Ltd. The samples referred to as NASA samples were woven in March 2002 and used by NASA in the Phase I ballistic testing. In addition, the Boeing tested samples [1] mentioned in this report were all taken from the same lot of weaved fabric used in the NASA Phase 1 ballistic testing. The samples referred to as ASU samples were woven in June 2004 and used by NASA in the Phase II ballistic testing. All tests conducted at ASU reflect the warp direction properties of the fabric – warp direction is also referred to as the 1 direction. Figure 1 shows the stress-strain curves for four (NASA) replicates tested in Feb 2006. Figure 2 shows the stress-strain curves for five (ASU) replicates tested in Feb 2005. Tables 2, 3 and 4 contain the summary of the test results for the ASU Samples (Test Date Feb 2005), NASA Samples (Test Date Feb 2006), and the ASU Samples (Test Date Feb 2006) respectively.
The stiffness value is the highest slope in the pre-peak region of the stress-strain curve. The toughness value reflects the area under the stress-strain curve.

Table 2. Summary of Fabric Properties (ASU Zylon 1500D Samples)
Test Date: Feb 2005

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Maximum Stress (MPa)</th>
<th>Toughness (MPa)</th>
<th>Stiffness, E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3285</td>
<td>58.3</td>
<td>148083</td>
</tr>
<tr>
<td>2</td>
<td>3412</td>
<td>62.7</td>
<td>152118</td>
</tr>
</tbody>
</table>
### Table 3. Summary of Fabric Properties (NASA Zylon 1500D Samples)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Maximum Stress (MPa)</th>
<th>Toughness (MPa)</th>
<th>Stiffness, E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2785</td>
<td>47.5</td>
<td>145404</td>
</tr>
<tr>
<td>2</td>
<td>2699</td>
<td>49.4</td>
<td>141602</td>
</tr>
<tr>
<td>3</td>
<td>2810</td>
<td>54.6</td>
<td>142927</td>
</tr>
<tr>
<td>4</td>
<td>2776</td>
<td>53.6</td>
<td>149649</td>
</tr>
<tr>
<td>Average</td>
<td>2768</td>
<td>51</td>
<td>144896</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>47.6</td>
<td>3.4</td>
<td>3539</td>
</tr>
</tbody>
</table>

### Table 4. Summary of Fabric Properties (ASU Zylon 1500D Samples)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Maximum Stress (MPa)</th>
<th>Toughness (MPa)</th>
<th>Stiffness, E (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2978</td>
<td>44.2</td>
<td>144898</td>
</tr>
<tr>
<td>2</td>
<td>3083</td>
<td>48.2</td>
<td>144482</td>
</tr>
<tr>
<td>3</td>
<td>2888</td>
<td>44.2</td>
<td>148025</td>
</tr>
<tr>
<td>4</td>
<td>2748</td>
<td>48.3</td>
<td>144507</td>
</tr>
<tr>
<td>5</td>
<td>3064</td>
<td>52.4</td>
<td>149795</td>
</tr>
<tr>
<td>Average</td>
<td>2952</td>
<td>47.5</td>
<td>146341</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>137.9</td>
<td>3.4</td>
<td>2432.5</td>
</tr>
</tbody>
</table>
Comparison of Tests Results

The test results show a noticeable decrease in the strength of the fabric with age. In a 12 month period, the maximum stress value shows a 9% decrease, the toughness a 22% decrease, and stiffness a small 2% decrease. Table 5 shows the properties obtained from various tests and sources for the Zylon 1500D fabric and the published fiber strength from Toyobo [1, 2]. It should noted that the Boeing values are from tests of a single warp or fill yarn whereas the ASU values reflect test results from a swatch of fabric.

Additional tests were run by Boeing on 500 denier Zylon samples from the same manufacturing lot. Table 6 summarizes the results which show the decrease in strength associated with the weaving process.

Table 5. Comparison of Fabric Properties Obtained From Various Sources

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Sample Description</th>
<th>Weave date</th>
<th>Test Date</th>
<th>Time (mo)</th>
<th>Max stress (MPa)</th>
<th>Toughness (MPa)</th>
<th>Stiffness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASU</td>
<td>1500D ASU (phase II) Warp</td>
<td>June 04</td>
<td>Feb 05</td>
<td>8</td>
<td>3240</td>
<td>61</td>
<td>149040</td>
</tr>
<tr>
<td>ASU</td>
<td>1500D ASU (phase II) Warp</td>
<td>June 04</td>
<td>Feb 06</td>
<td>20</td>
<td>2952</td>
<td>47.5</td>
<td>146341</td>
</tr>
<tr>
<td>Boeing</td>
<td>1500D NASA (phase I) Warp</td>
<td>Mar 02</td>
<td>Nov 02</td>
<td>8</td>
<td>3448</td>
<td></td>
<td>140556</td>
</tr>
<tr>
<td>Boeing</td>
<td>1500D NASA (phase I) Fill</td>
<td>Mar 02</td>
<td>Nov 02</td>
<td>8</td>
<td>3291</td>
<td></td>
<td>146035</td>
</tr>
<tr>
<td>ASU</td>
<td>1500D NASA (phase I) Warp</td>
<td>Mar 02</td>
<td>Feb 06</td>
<td>47</td>
<td>2768</td>
<td>51</td>
<td>144896</td>
</tr>
<tr>
<td>Toyobo</td>
<td>Web site fiber properties</td>
<td></td>
<td></td>
<td>5800</td>
<td></td>
<td>180000</td>
<td></td>
</tr>
</tbody>
</table>

Information in Table 5 is presented in a graphical form in figures 3 and 4. The effects of weaving and aging are shown in Table 6.
Figure 3. Variation in max. stress as a function of time
Figure 4. Variation in stiffness as a function of time

Table 6. Comparison of 500 Denier 35x35 Zylon Showing Effects of Weaving and Aging

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Sample Description</th>
<th>Weave Date</th>
<th>Test Date</th>
<th>Time (mo)</th>
<th>Max stress (MPa)</th>
<th>Toughness (MPa)</th>
<th>Stiffness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing</td>
<td>500D (phase I) Warp</td>
<td>Mar 02</td>
<td>Nov 02</td>
<td>8</td>
<td>3135</td>
<td>142747</td>
<td></td>
</tr>
<tr>
<td>Boeing</td>
<td>500D (phase I) Fill</td>
<td>Mar 02</td>
<td>Nov 02</td>
<td>8</td>
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Hypothesis Testing (t-Test)

Hypothesis testing (t-Test) is conducted on the ASU Test results to ascertain if the mean of the maximum stress value in the sample sets can be assumed to be the same or if they are different. The two hypotheses considered are as follows.

Null Hypothesis, H0: Mean of Samples 1 = Mean of Samples 2  
Alternate Hypothesis, H1: Mean of Samples 1 ≠ Mean of Samples 2

A 95% confidence level corresponding to a significance level as 0.05 is used in the following analysis. Two tests are carried out - the difference in mean between ASU Samples tested in Feb 05 and NASA Samples tested in Feb 06, and the difference in mean between ASU Samples tested in Feb 05 and ASU Samples tested in Feb 06.

Test 1 (ASU Samples tested in Feb 05 and NASA Samples tested in Feb 06)
Since, the standard deviation of maximum stress from NASA samples (47.6) is significantly less than the ASU samples’ standard deviation (132), t-Test model for different standard deviations is adopted.

Sample size of ASU Samples tested in Feb 05, \(n_1 = 5\)  
Sample size of NASA Samples tested in Feb 06, \(n_2 = 4\)

Standard deviation of ASU Sample set tested in Feb 05, \(s_1 = 132.2\)  
Standard deviation of NASA Sample set tested in Feb 06, \(s_2 = 47.6\)

ASU Sample (max. stress), \(m_1 = 3240.3\) MPa  
NASA Sample (max. stress), \(m_2 = 2767.5\) MPa

\[
t_0 = \frac{(m_1 - m_2)}{\sqrt{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}}
\]

(1)

\[
v = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}{\left(\frac{s_1^2}{n_1-1} + \frac{s_2^2}{n_2-1}\right)}
\]

(2)
\( t_{\alpha/2, v} \) can be found from the t-table where \( \alpha \) is the significance level (taken as 0.05). Rejection criteria for NULL hypothesis is \( |t_0| > t_{\alpha/2, v} \).

From above data, \( t_0 = 7.417 \) and \( t_{\alpha/2, v} = 2.447 \).

Since \( |t_0| > t_{\alpha/2, v} \), the Null hypothesis H0 is rejected and alternate hypothesis H1 holds good. Thus the two samples have different mean values.

**Test 2 (ASU Samples tested in Feb 05 and ASU Samples tested in Feb 06)**

Since the standard deviation of maximum stress for these two sample sets are identical, t-Test model for same standard deviation is adopted.

Sample size of ASU Samples tested in Feb 05, \( n_1 = 5 \).

Sample size of ASU Samples tested in Feb 06, \( n_2 = 5 \).

Standard deviation of ASU Samples tested in Feb 05, \( s_1 = 132.2 \).

Standard deviation of ASU Samples tested in Feb 06, \( s_2 = 137.9 \).

ASU Sample tested in Feb 05 (max. stress), \( m_1 = 3240.3 \text{ MPa} \).

ASU Sample tested in Feb 06 (max. stress), \( m_2 = 2952 \text{ MPa} \).

\[
t_0 = \frac{(m_1 - m_2)}{s_p \sqrt{\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \quad \text{where} \quad s_p = \sqrt{\left(\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}\right)}
\]

(3)

\[
\nu = n_1 + n_2 - 2
\]

(4)

\( t_{\alpha/2, v} \) can be found from the t-table where \( \alpha \) is the significance level (taken as 0.05). Rejection criteria for Null hypothesis is \( |t_0| > t_{\alpha/2, v} \).

From above data, \( t_0 = 3.37 \) and \( t_{\alpha/2, v} = 2.306 \).

Since \( |t_0| > t_{\alpha/2, v} \), NULL hypothesis H0 is rejected and alternate hypothesis H1 holds good. Thus the two samples have different mean values.

**References**

