LOW VELOCITY IMPACT OF COMPOSITE AEROSTRUCTURES

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   While considerable effort has been put into understanding the low-velocity impact of composite
   laminates, there is still considerable uncertainty concerning the analysis tools required to give accurate
   predictions of stresses and strains for design purposes. It has been determined that elastic bending
   solutions are inaccurate, and that several phenomena may explain the differences observed between elastic
   theory and experiment. These are:

   1. Contact deformations
   2. Transverse shear deformations
   3. Viscoelasticity
   4. Large deflections and membrane effects.

   The objective of this project is to determine if and under what conditions each of the four phenomena
   must be modeled in analyses of low-velocity impact of fiber composite laminated structures.

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FEAP74, a finite element code developed for USDOT to treat contact-impact problems, was secured for the analytical portion. Viscoelastic and large deflection elements in the code were defective, and analysis was limited to elastic impact. The program was used to analyze a considerable number of long, laminated plates clamped on two parallel edges. The analysis treated flexure, contact, and transverse shear deformations together and separately to obtain the relative orders of magnitude of each effect.

Tests were designed to duplicate the conditions of the analysis. AS-3501 graphite/epoxy plate samples were fabricated and tested using the NAVAIRDEVCEN impact tower with automated data storage and manipulation capabilities. Each test specimen was strain gaged so that time-histories of back-surface strain could be measured and compared with analysis.

The program has shown that flexural viscoelasticity is negligible, but that viscoelastic transverse shear and contact deformations are important for short composite plates. It appears that membrane effects may be important for longer plates where strains are significantly underpredicted by elastic small-deflection analysis. These results will give guidance to analysts who must predict strains and stresses in order to achieve safe, efficient, impact-resistant composite structures.

Since previous creep data on AS-3501 graphite/epoxy material was determined using minutes as data intervals, it was unsuitable for time frames of a fraction of a second which represent duration of impact loading. The determination under this program of an experimental viscoelastic creep compliance for AS-3501 graphite/epoxy material will provide analytical viscoelastic models with accurate property data with which to analyze laminates undergoing low-velocity impact.
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I. INTRODUCTION

Laminated fiber composites, used extensively in military aircraft, can be damaged by impact of blunt, hard objects such as stones or dropped tools. It is necessary to be able to analyze these structures and design them to resist impact damage. For low velocity impact where wave propagation may not play a role, it has not been established under what conditions certain effects need to be included in analyses. The most important of these appear to be contact deformation between impactor and structure, transverse shear deformations, viscoelastic material behavior, and large deformation (membrane) effects. The research reported here was undertaken to determine the relative importance of these phenomena in predicting the impact response of laminated composites.

There are several types of blunt object impact damage which can occur in laminated composites [1-3]:

- penetration caused by high-velocity impact;
- crushing of impacted surface material, delamination, and shattering of the back surface at moderate velocities which is caused by the interaction of elastic wave effects and quasistatic structural stresses; and
- a combination of flexural cracking and interply damage which can occur at low impactor velocities and may not involve wave propagation effects.

It is the incipient damage caused by low velocity, blunt object, transverse impact with which this report is concerned.

*Numbers in square brackets identify references.
Several investigators have researched the problem. Chou and Flis [4] have shown that analysis of beam and plate structures considering only flexure and static deflection shapes can give non-conservative predictions of structural strains. They also show [4, 5] that solving problems dynamically but still treating only flexure as was done by McQuillen, Llorens, and Gause [6] and Hayes and Rybicki [7] significantly overpredicts the strains. Llorens, McQuillen, and Gause [8, 9, 10] attempted to correct this overprediction using exact and approximate viscoelastic damping, but were only partially successful: non-conservative results were obtained in several cases. It was demonstrated [4] that treatment of Herzian contact deformation between impactor and structure as was done by Sun and Chattopadhyay [11], Bostaph and Elber [12], and Elber [13] also tends to correct the elastic flexural overpredictions, but direct comparison with experimental data was not available.

There is an uncertainty whether viscoelastic structural damping or Hertzian contact deformation is more important to achieving accurate predictions of structural strains in low-velocity impact of composite beams and plates. References [12] and [13] show that membrane force effects can also play an important role in obtaining accurate predictions of stresses and deformations in thin composite plates undergoing impact. It is also well-known that transverse shear deformations can be important for thick plates. Several researchers [10, 14-16 for example] have used finite element methods to analyze composite laminate impact problems, some including the effects of elastic contact stress [14, 15], contact deformation [16] and transverse shear deformation [14-16]. Several
of the methods were semi-empirical or approximate and have not been substantiated by experimental evidence. None has investigated the relative importance of structural viscoelasticity, contact stresses, transverse shear deformations, and membrane effects.

A program of analysis and experiment was initiated to investigate under what conditions each of the four phenomena described above may be important to analyzing composite structures. The program consisted of:

1. An investigation into viscoelastic properties of composites to determine which were the most likely modes of viscoelastic dissipative mechanisms during impact and to determine the short-time viscoelastic properties of AS-3501 graphite/epoxy.


The original plan was to analyze AS 3501 graphite/epoxy composite beams using the FEAP74 finite element code [17-23]. The code was developed for the U. S. Department of Transportation for impact studies and contains 3-D, 2-D, shell (with transverse shear), and contact elements; viscoelasticity; orthotropy; and large displacements. When received, the program was found to be defective in the viscoelasticity and large deflection shell elements. Also, the viscoelastic element was not orthotropic. As a result, the analysis portion of the program was limited to elastic finite element analysis which treated elastic shear and contact deformations. The analyses were used to evaluate the relative importance of these effects on prediction of strains and to provide an analytical baseline for comparison with tests.
In order to evaluate the accuracy of elastic analysis predictions for behavior of laminated composites undergoing impact, tests were conducted on specially fabricated AS-3501 graphite/epoxy plates using the NAVAIRDEV/CEN instrumented impact tower. Results of the tests were compared with the finite element analyses, and conclusions were drawn concerning the need for including transverse shear, contact, and other deformation phenomena in an impact analysis capability.

This report presents analysis and test work performed under the program, recommends a viscoelastic model of AS-3501 composite plates for use in impact analysis, and draws conclusions concerning the importance of elastic and viscoelastic behavior to impact analysis of composite laminates.
II. VISCOELASTIC BEHAVIOR OF COMPOSITE LAMINATES

A. DISSIPATIVE MECHANISMS DURING IMPACT

The work of Llorens, McQuillen, and Gause [8 - 10] has demonstrated that an energy absorption mechanism other than elastic flexure is active during low-velocity impact (less than 9 m/s or 30 ft/s). Their analysis and comparison with test data for impacted AS-3501 plates show that flexural viscoelastic analysis compares much better with experimental results than purely elastic flexural analysis. However, there are still large discrepancies for certain plate aspect ratios indicating that the energy absorption mechanism may not be flexural, and that perhaps a different viscoelastic model might improve accuracy of analytical predictions.

1. Flexural Viscoelasticity of AS-3501 Graphite/Epoxy

It is well-known [24-27, for example] that, for a unidirectional composite consisting of high-stiffness elastic fibers in a viscoelastic polymeric matrix, the effective viscoelastic composite behavior is most pronounced under transverse normal stress $\sigma_{22}$, transverse shear stress $\tau_{13}$ and $\tau_{23}$, and axial shear stress $\tau_{12}$ (Figure 1). Viscoelastic behavior will be exhibited under axial normal stress, but, due to the dominance of the high-stiffness elastic fibers, it can be negligible compared to the other modes. In plate bending, however, the mode of deformation can be predominately flexure and it may be that axial normal viscoelasticity alone can be great enough to explain test results on impacted plates.
Figure 1. Unidirectional fiber composite stresses.
In order to see if viscoelastic behavior of AS-3501 graphite/epoxy under axial normal stress is great enough to give the flexural viscoelastic behavior required to correlate analysis with test data [8 - 10], viscoelastic properties of AS-3501 obtained from the tests of Renton and Ho [28] were analyzed and compared with the flexural viscoelastic properties used in references [8 - 10].

a. Matrix Shear Power Law Creep Compliance [28]. Renton and Ho [28] have done tensile creep tests of [±45]₅ laminates of AS-3501 and have used a power law creep compliance given by

\[ \frac{e}{s} = D_0 + D_1 t^n \]  \hspace{1cm} (1)

where
\[
\begin{align*}
e &= \text{tensile strain} \\
s &= \text{tensile stress} \\
t &= \text{time} \\
D_0, D_1, \text{ and } n &= \text{viscoelastic constants.}
\end{align*}
\]

Under all environments, \( n = 0.18 \) gave good correlation with test data. The constants \( D_1 \) and \( D_0 \) for room temperature tests at 50% relative humidity were found to be

\[
\begin{align*}
D_0 &= 3.412 \times 10^{-7} \text{ in}^2/\text{lb} \{(4.949 \times 10^{-5}) \text{ MPa}^{-1}\} \\
D_1 &= 0.108 \times 10^{-7} \text{ in}^2/\text{lb} \{(0.155 \times 10^{-5}) \text{ MPa}^{-1}\}
\end{align*}
\]

Using laminate analysis and assuming that the Halpin-Tsai equations relating constituent properties to composite properties are valid, Renton and Ho construct a nomogram by which the matrix
shear creep compliance, $F_M$, can be obtained from $[±45]$ tensile creep compliance. Using the values of $D_0$ and $D_1$ given above and Figure 24 of Reference [28], the following relationship is obtained for room-temperature matrix shear creep compliance:

\[
F_M = 9.30(10^{-6}) + 0.340(10^{-6})t^{0.18} \text{ in}^2/\text{lb} \tag{2}
\]

\[
= 13.5(10^{-4}) + 0.493(10^{-4})t^{0.18} \text{ MPa}^{-1}
\]

b. Matrix Extensional Power Law Creep Compliance. - Even if matrix isotropy is assumed, one must know the bulk creep compliance or the creep Poisson compliance to be able to determine the extensional creep compliance, $D_M$ of the matrix [27]. However, for an order-of-magnitude estimate, it is assumed that Poisson's ratio $v_M$ remains constant with time at a value of 0.3. For isotropic behavior, this results in an extensional creep compliance for the matrix of

\[
D_M = 0.5F_M/(1 + v_M)
\]

\[
= 3.58(10^{-6})(1 + 0.03656t^{0.18}) \text{ in}^2/\text{lb} \tag{3}
\]

\[
= 5.19(10^{-4})(1 + 0.03656t^{0.18}) \text{ MPa}^{-1}
\]

c. Unidirectional Composite Extensional Creep Compliance. - Assuming isotropic, linear elastic fibers with Poisson's ratio of 0.3, the effective axial creep compliance $D^*$ of a unidirectional composite with fiber volume fraction $V_F$ is

\[
D^* = [V_F/D_F + (1 - V_F)/D_M]^{-1} \tag{4}
\]
For AS-3501, fiber volume fraction is $V_F = 0.62$. Fiber modulus can be calculated from equation (3) with $t = 0$ and equation (4) with composite initial modulus $1/D^* = 21.0$ Mlb/in$^2$ (145 GPa). The result is $1/D_F = 33.75$ Mlb/in$^2$ (232.7 GPa). For arbitrary time, (4) gives

$$D^* = 4.75(10^{-8})(1 + 0.03656t^{0.18})/(1 + 0.03637t^{0.18}) \text{ in}^2/\text{lb} \quad (5)$$

$$= 6.90(10^{-6})(1 + 0.03656t^{0.18})/(1 + 0.03637t^{0.18}) \text{ MPa}^{-1}$$

as the axial creep compliance of unidirectional AS-3501.

**d. Laminate Extensional Creep Compliance Power Law Approximation.** In order to compare the viscoelastic properties of AS-3501 to those used for impacted plate experimental correlation in [8-10], it is noted that the extensional moduli of the multidirectional laminates used in [8-10] are approximately half that of the unidirectional composite. Assuming that equation (4) will approximate the shear creep compliance of the multidirectional plate if $2D_F$ is used in place of $D_F$, the following equation is obtained for an order-of-magnitude estimate of plate extensional creep compliance $D_p^*$:

$$D_p^* = 9.46(10^{-8})(1 + 0.03656t^{0.18})/(1 + 0.03619t^{0.18}) \text{ in}^2/\text{lb} \quad (6)$$

$$= 13.72(10^{-6})(1 + 0.03656t^{0.18})/(1 + 0.03619t^{0.18}) \text{ MPa}^{-1}$$

Another order-of-magnitude estimate would be to double the unidirectional axial creep compliance (5). This results in an approximation which is numerically very close to equation (6);
therefore, (6) will be used as the laminated plate extensional creep compliance.

e. Exponential Approximation of Laminate Extensional Creep Compliance. - Since the viscoelastic creep function assumed in the plate analysis of references [8-10] is an exponential law, it is desirable to take the power law creep compliance (6) obtained from Renton and Ho's data and fit it to an exponential three-parameter viscoelastic solid having a creep relaxation function of

\[ D_p^{*RH} = \frac{1}{q_1} + \left( \frac{p}{q_2} - \frac{1}{q_1} \right) \exp\left[ -\frac{q_1 t}{q_2} \right] \]  \hspace{1cm} (7)

where \( q_1, q_2, \) and \( p \) are viscoelastic constants. Fitting (7) to (6) at \( t = 0 \) s, 1.0 s, and infinity gives the following values for the constants

- \( q_1 = 10.46 \text{ Mlb/in}^2 \text{ (72.13 GPa)} \)  
- \( q_2 = 294. \text{ Mlb.s/in}^2 \text{ (2029. GPa.s)} \)  
- \( p = 27.85 \text{ s} \)  \hspace{1cm} (8a,b,c)

It is noted that these creep compliance calculations are approximate and are to be used for order-of-magnitude comparisons only!

2. Flexural Viscoelasticity Required to Correlate Impact Data

The flexural viscoelastic constitutive relation used by Llorens, McQuillen, and Gause[8-10] to correlate plate impact data is equivalent to a Kelvin solid having the following extensional creep compliance:

-10-
\[ D_{p,LMG}^* = \left(1/q_3\right)\left(1 - \exp[-q_3 t/q_4]\right) \]  

(9)

which has the form of (7), but with \(p = 0\). Their analysis of impacted plates correlates with tests of AS-3501 laminates when

\[ q_4/q_3 = 25(10^{-6}) \text{s to } 100(10^{-6}) \text{s}. \]  

(10a)

For an accurate comparison between (9) and (7), it is necessary that

\[ q_3 = q_1 \]  

(10b)

In order to compare the amount of extensional viscoelasticity required by Llorens, McQuillen, and Gause to correlate their test data with the extensional viscoelasticity available from AS-3501 as determined above from the tests of Renton and Ho, it is desirable to have a quantitative measure of damping which is not heavily dependent upon the form of the assumed viscoelastic constitutive relation. The amount of energy per unit volume dissipated in one cycle of sinusoidal loading, \(EDC\), is one such convenient quantity which is calculated from the equation [29, 30]

\[ EDC = T w (q_B - q_A p) s_0^2 / (q_A^2 + q_B^2 w^2) \]  

(11)

where

- \(w\) = loading frequency
- \(q_A, q_B, p\) = viscoelastic constants (\(A = 1\) or 3, \(B = 2\) or 4)
- \(s_0\) = stress half-amplitude
The ratio of energy density dissipated per cycle using the material behavior required to correlate plate impact data (EDC_{LMG}) to that which has been calculated using known AS-3501 material behavior (EDC_{RH}) becomes

$$\frac{\text{EDC}_{LMG}}{\text{EDC}_{RH}} = \frac{q_4 (q_1^2 + q_2^2 w^2)}{(q_3^2 + q_4^2 w^2)(q_2 - q_1 p)}$$  \hspace{1cm} (12)$$

and should tell if flexural viscoelasticity or some other energy absorption mechanism is dominating impact behavior.

The tests of Chou, Flis, and Miller [31] were used to correlate the analysis of [8-10]. These tests had typical impact event times of 5 ms which are equivalent to an oscillatory period of 10 ms and a cyclic frequency \(w\) of approximately 600 rad/s. Using this frequency and a representative value of \(q_4/q_3 = 60\) s, equations (8), (10), and (12) give

$$\frac{\text{EDC}_{LMG}}{\text{EDC}_{RH}} = 6(10^4)$$  \hspace{1cm} (13)$$

Clearly, the degree of flexural viscoelastic behavior required to fit impact data is several orders of magnitude greater than that which exists in the material. It is concluded that the energy absorbing mechanism cannot be flexural viscoelasticity. The determination and modeling of the true cause(s) of the disparity between elastic impact analysis and test data may provide better correlation between analysis methods and tests and yield guidelines for more accurate design approaches to impact resistance.
3. Impact Energy Absorbing Mechanisms

Energy absorbed by composite plates during impact is not entirely due to elastic flexure, and Llorens, McQuillen, and Gause have shown that other mechanisms are operative. The preceding analysis has shown that flexural viscoelasticity is negligible and that other energy absorptive phenomena must be treated in order to obtain good analytical predictions for design purposes. As presented in the introduction to this report, the following mechanisms are considered to be the strongest candidates:

1. Contact deformations between impactor and plate.
2. Transverse shear deformations.
3. Membrane forces.

Of these, the membrane force effects are known to be important whenever plate deflections exceed plate thickness (methods of treatment of large deflections of thin composite laminates during impact analysis have been described by Elber and Bostaph [12,13], for example). Shorter, thicker plates appear to require treatment of contact deformations and/or transverse shear deformations.

Both contact deformations and transverse shear deformations are matrix-dominated phenomena, i.e., the properties of the matrix material will control laminate behavior in these modes. Fiber-dominated laminates are therefore stiff in flexure (or any other in-plane deformation mode such as membrane stretching), but may be relatively flexible under transverse normal stress and transverse shear stress. Transverse normal stress effects will control contact deformations induced by hard impactors. For composites, transverse shear effects can be important for relatively thin plates. For example, it is well-known that the
deflection, $u$, of a cantilevered wide plate under a concentrated transverse load, $P$, at its tip can be approximated by strength-of-materials analysis as

$$u = \frac{PL^3}{3EI}(1 + 0.25Ch^2/GL^2)$$

where

$L =$ plate length
$h =$ plate thickness
$I =$ $wh^3/12$, $w =$ plate width
$G =$ material transverse shear modulus
$C =$ plate extensional modulus

The last term in the last parentheses represents the contribution of transverse shear deformation to deflection. For isotropic materials where $E$ and $G$ are the same order of magnitude, the transverse shear deflection will be no more than 3% of the total if length $L$ is longer than $5h$. For a typical graphite epoxy, $L$ must be greater than $20h$ for the same relative magnitude of shear deflection.

In addition, since polymeric matrix behavior is viscoelastic, it is possible that treatment of elastic transverse normal and shear is insufficient: viscoelastic contact deformations and transverse shear deformations may need to be modeled in order to obtain reasonable analytical accuracy for design or analysis purposes.
B. VISCOELASTIC PROPERTIES OF AS-3501

1. Viscoelastic Material Modeling

It has been demonstrated here and elsewhere that in-plane stress-strain relations can be elastic without loss of accuracy for low-velocity plate impact analysis. In order that a plate exhibit contact deformation viscoelasticity and transverse shear viscoelasticity, it will be necessary to model transverse normal and shear stress-strain relations as viscoelastic. An elementary model which would take the major effects into account although it may not be thermodynamically correct is to assume that composite transverse normal and shear viscoelastic relations are uncoupled and have the following exponential relaxation functions:

\[
G_T = G_0 + G_1 \exp\left(-\frac{t}{b}\right) \quad \text{(shear)} \tag{14}
\]
\[
C_T = C_0 + C_1 \exp\left(-\frac{t}{a}\right) \quad \text{(normal)} \tag{15}
\]

where \(C_0, G_0, C_1, G_1, a, \) and \(b\) are constants.

This would allow use of certain finite element codes which use this functional form ([17], for example, with appropriate code modification for orthotropy).

In order to obtain the three material constants required in each of equations (14) and (15), tests must be performed. The most efficient way to obtain shear properties for equation (14) is to perform a creep test of a \([\pm 45]_S\) laminate in tension as was done by Renton and Ho [28]. The creep compliance thus obtained can be inverted to give the relaxation modulus (14) by Laplace transform techniques using the correspondence principle of linear
viscoelasticity [27, for example]. Using relationships developed between matrix, fiber, and composite viscoelastic stress-strain relations [24, 27], one may determine matrix viscoelastic stress-strain relations from composite shear behavior and in turn use the matrix behavior to calculate the transverse normal viscoelastic relaxation modulus (15)(see reference [28] for one description of this process).

Experimentally, then, creep tests on $[\pm 45]$ tension specimens are sufficient to determine any viscoelastic properties that may be important to impact analysis of composite laminates. All multidirectional laminates of the same unidirectional material have approximately the same transverse normal and shear behavior since stacking sequence affects only in-plane constitutive relations.

The time from impact to rebound or fracture will depend upon material stiffness properties, structural geometry, and impactor mass. During low-velocity impact of aircraft skins by stones, tools, or other similar-size masses, this elapsed time is seldom greater than 0.05 s and can be considerably shorter. The viscoelastic test data for $[\pm 45]$ AS-3501 graphite/epoxy laminates generated by Renton and Ho [28] used creep data intervals of one minute (60 s). Since the impact events are taking three orders of magnitude less time than the first data point in [28], the use of Renton and Ho's data for accurate viscoelastic deformation calculations is questionable.

The following section describes tests performed to determine the shear relaxation modulus of AS-3501 graphite/epoxy for use during short time intervals typical of impact occurrences.
2. Test Program

In order to develop viscoelastic properties which might be valid over time intervals on the order of fractions of a second, a series of high-speed creep tests was performed on $[\pm45]_{2S}$ AS-3501 using an Instron servohydraulic tensile test machine at the laboratories of the Naval Air Development Center.

Each specimen was 0.5 in (25.4mm) wide and 9.0 in (225 mm) long and was appropriately tabbed with glass end tabs. Each was instrumented with a 3-element rectangular strain gage rosette with the middle gage in the direction of loading and the other two at angles of $+45^\circ$ and $-45^\circ$ to the loading direction.

Load and axial strain were read into a Nicolet digital storage scope, and the $45^\circ$ strain gages were monitored by a Tektronix fluorescent storage oscilloscope. Photographic records of 45 strains were made with a Polaroid camera fitted to the Tektronix scope.

Specimens were "instantaneously" ramp-loaded to a predetermined load (ranging from 125 lb [556 N] to 640 lb [2.85 kN]) and held at this constant load for approximately ten minutes. During the first twenty seconds, 2,000 data points were recorded by the Nicolet storage scope for both load and strain. This provided 10 data points in the first 0.1 s which is considerably better than one data point every 60 s. Twenty-second data records were also made after approximately five minutes and ten minutes, respectively, to obtain long-time creep information.
3. Test Results

Typical creep test data are presented in Figures 2, 3, and 4 which give axial load and strain for the first twenty seconds, the twenty second interval beginning after an elapsed time of five minutes, and the twenty second interval after an elapsed time of thirteen minutes, respectively.

It was found that during the initial loading, approximately two data intervals of 0.01 s were required for the test machine to reach the desired load, and another 28 data intervals for the hydraulics to stabilize the load (one or two "dips" of about 4% from the preset load typically occurred). The strain data was adjusted for the load variations by multiplying the strain at a given time by the ratio of actual load at that time to the stable load reached after 0.5 s. Also, as is evident in Figure 2, noise was superimposed on the strain signal. Data were assumed to lie midway between noise peaks. Figure 5 shows the results of adjusting and smoothing the data from Figure 2 (note the expanded time scale in Figure 5).

Adjusted extensional strain data in the $0^o$, $+45^o$, and $-45^o$ directions from the strain gage rosette were transformed using the common plane transformation equations to yield the axial shear strain (parallel to fiber directions). Load was divided by the $[\pm45]$ specimen cross-sectional area to obtain tensile stress which was then transformed to axial shear stress (parallel to fiber direction - Figure 1). The resulting shear stress and time history of shear strain were analyzed to determine axial shear relaxation modulus as follows:
Figure 2. Load and axial strain vs. time during creep test of [$\pm45\]$ AS-3501 graphite/epoxy tension specimen under 122 lb (543 N) load. Time interval 0.0 s to 20 s.
Figure 3. Load and axial strain vs. time during creep test of \([\pm 45]\) AS-3501 graphite/epoxy tension specimen under 122 lb (543 N) load. Time interval 300 s to 320 s.
Figure 4. Load and axial strain vs. time during creep test of [±45] AS-3501 graphite/epoxy tension specimen under 122 lb (543 N) load. Time interval 780 s to 800 s.
Figure 5. Adjusted axial strain vs. time for creep test of [±45] AS-3501 graphite/epoxy tension specimen under 125 lb (556 N) load. Time interval 0.0 s to 20 s.
The form of shear relaxation modulus chosen was that of equation (14) which has three viscoelastic constants - the static (slow load) shear modulus $G_0$, the viscous modulus $G_1$, and the exponential decay parameter, $b$:

$$G_{12} = G_0 + G_1 \exp(-t/b)$$ (16)

It can be shown that the shear creep compliance corresponding to this relaxation modulus is

$$F_{12} = 1/G_0 - G_1[G_0(G_0 + G_1)]^{-1}\exp(-t/c)$$ (17a)

where

$$c = b(G_0 + G_1)/G_0$$ (17b)

The static shear modulus $G_0$ was determined from slow-speed tension tests of specimens similar to those used for creep tests. The ratio of viscous modulus $G_1$ to shear modulus $G_0$ was calculated from the equation

$$G_1/G_0 = G_D/G_0 - 1$$ (18)

where $G_D$ is the dynamic shear modulus found from high-speed test data. In this case, $G_D$ was determined from plots of stress versus strain obtained from the initial 0.05 s of creep data. With $G_0$ and $G_1$ known, the exponential creep decay parameter, $c$, was found by choosing one point on the adjusted extensional strain curve and solving for $c$ from equation (17a). The exponential relaxation decay parameter $b$ was then determined from equation (17b).
The parameter $b$ was calculated from several points on the initial portion of the creep strain curve and was found to be affected by the point chosen for its determination. The most consistent results were obtained when data points were taken within the first 0.3 s of creep data where the majority of the creep strain took place.

Computed relaxation modulus constants obtained from the viscoelastic creep tests are presented in Table 1. Appendix A contains computer-generated plots of the creep data from the tests.

Table 1. Relaxation Modulus Constants for AS-3501 in Axial Shear.

<table>
<thead>
<tr>
<th>Relaxation Modulus Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_0$</td>
<td>0.941(10^6) lb/in^2 [6.49 MPa]</td>
</tr>
<tr>
<td>$G_1/G_0$</td>
<td>0.0313</td>
</tr>
<tr>
<td>$b$</td>
<td>$0.15 + 0.05$ s⁻¹</td>
</tr>
</tbody>
</table>
III. ELASTIC ANALYSIS OF IMPACTED COMPOSITE BEAMS

A. FINITE ELEMENT MODEL

1. Structural Configuration and Material Properties

Elastic analysis of AS-3501 graphite/epoxy composite plate structures was performed to determine the relative effects of contact deformations and transverse shear deformations, and to provide an analytical baseline for comparison of data from impact tests. For both analytical and experimental simplicity, a long plate clamped at both ends was chosen. Plates ranged in length from 2.56 in (65 mm) to 13.98 in (355 mm), but all plates were 1.57 in (40 mm) wide. Plates had thicknesses of 1/8 in (3 mm) or 1/4 in (6 mm) corresponding to 24- and 48-plies of AS-3501, respectively. Figure 6 illustrates plate configurations analyzed.

The actual stacking sequences used in impact tests which the finite element analysis was designed to model were $[(\pm 45/0_2)_2/\pm 45/0/90]_S$ and $[(\pm 45/0_2)_2/\pm 45/0/90]_2S$. For the model, each plate was assumed to have uniform orthotropic elastic constants corresponding to $[\pm 45/0_2]_NS$ stacking sequences of AS-3501 graphite/epoxy. Laminate analysis confirmed that axial strains in a plate contained less than 1% error with the uniform material assumption compared to individual ply modeling.

The major material axis was chosen to be oriented at either 0° or 90° to plate longitudinal axis for each of the four plate geometries, which gave a total of eight plates to be analyzed. Figure 6 presents geometry, material, and associated numbering system details.
<table>
<thead>
<tr>
<th>PLATE ID</th>
<th>LENGTH L in/mm</th>
<th>WIDTH W in/mm</th>
<th>THICKNESS h in/mm</th>
<th>STACKING SEQUENCE (X = 0^\circ)</th>
<th>MATERIAL CODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>14/355</td>
<td>1.57/40</td>
<td>.128/3.25</td>
<td>([ \pm 45/0^\circ ],\pm 45/0^\circ )</td>
<td>H</td>
</tr>
<tr>
<td>I2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>([ \pm 45/90^\circ ],\pm 45/90^\circ )</td>
<td>L</td>
</tr>
<tr>
<td>I3</td>
<td>5.31/135</td>
<td>&quot;</td>
<td>&quot;</td>
<td>([ \pm 45/90^\circ ],\pm 45/90^\circ )</td>
<td>H</td>
</tr>
<tr>
<td>I4</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>([ \pm 45/90^\circ ],\pm 45/90^\circ )</td>
<td>L</td>
</tr>
<tr>
<td>I5</td>
<td>&quot;</td>
<td>&quot;</td>
<td>.256/6.5</td>
<td>([ \pm 45/0^\circ ],\pm 45/0^\circ )</td>
<td>H</td>
</tr>
<tr>
<td>I6</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>([ \pm 45/90^\circ ],\pm 45/90^\circ )</td>
<td>L</td>
</tr>
<tr>
<td>I7</td>
<td>2.56/65</td>
<td>&quot;</td>
<td>&quot;</td>
<td>([ \pm 45/0^\circ ],\pm 45/0^\circ )</td>
<td>H</td>
</tr>
<tr>
<td>I8</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>([ \pm 45/90^\circ ],\pm 45/90^\circ )</td>
<td>L</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MATERIAL CODE</th>
<th>AVERAGE PLANE STRAIN ELASTIC CONSTANTS* Mpsi (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_{XX} )</td>
</tr>
<tr>
<td>H - High Stiffness in X Direction</td>
<td>11.2(75.4)</td>
</tr>
<tr>
<td>L - Low Stiffness in X Direction</td>
<td>5.45(37.6)</td>
</tr>
</tbody>
</table>

* Normal Stress \( s \) and Strain \( e \):
\[
\begin{align*}
  s_{XX} &= C_{XX} e_{XX} + C_{XZ} e_{ZZ} \\
  s_{ZZ} &= C_{XZ} e_{XX} + C_{ZZ} e_{ZZ}
\end{align*}
\]
Shear Stress \( s_{XZ} \) and Strain \( e_{XZ} \):
\[
  s_{XZ} = C_{SS} e_{XZ}
\]
(Note that \( e_{XZ} \) is tensorial shear strain)

Figure 6. Structural and material configurations analyzed by FEAP74 finite element code.
Since plates were an order of magnitude wider than they were thick, a two-dimensional plane strain analysis was appropriately selected for the impact analyses. In order to determine the effects of elastic contact deformations and transverse shear deformations on analysis results, transverse material properties were altered and finite element analyses were run in the following sequence:

a. full two-dimensional orthotropic elasticity which contained the effects of flexure, elastic contact deformations, and elastic transverse shear deformations.

b. transverse normal stiffness was increased by two orders of magnitude which eliminated contact deformations but maintained flexure and transverse shear effects.

c. both transverse normal and transverse shear stiffnesses were increased by two orders of magnitude which eliminated contact and transverse shear deformations but maintained flexural effects.

2. Finite Element Code

The finite element code chosen for the analysis was FEAP74, a program developed by University of California, Berkeley, for the U. S. Department of Transportation especially for contact-impact problem analysis. The code contains operational two- and three-dimensional orthotropic elastic elements, laminated orthotropic plate element, and contact elements. Dynamic impact problems can be analyzed using explicit or implicit finite difference formulations in the time domain. The implicit option was chosen since results thus obtained are always stable and convergent.
Unfortunately, large deflection plate and viscoelastic elements were inoperable in the version received from Cal-Berkeley. While these elements were not able to be made operational, several other errors were found in the code and corrected so that the other elements will run with the implicit dynamic analysis option. The version currently on tape storage at the NADC computer facility contains all corrections which were made.

3. Finite Element Mesh Construction

In order to prevent possible numerical instabilities during the finite element analyses, care was taken to construct elements having nearly equal stiffnesses in the principal directions. Plane strain meshes sized from 64 elements and 87 nodes to 383 elements and 462 nodes were analyzed for optimal accuracy and running time. It was found that less than 3% difference in pertinent stresses and strains was obtained between meshes having four elements through the beam thickness and six elements through the beam thickness. Accordingly, four-element-thick beam meshes were used for the finite element production runs.

The impactor from the NADC impact tower required less precision in modeling than did the plates. Force in the load cell of the impactor was the quantity of interest since time histories of the load could be obtained during tests. Care was taken to model the impactor tip so that accurate contact stresses would be obtained, but the remaining parts (load cell, tip connector, frame, and guides) were modeled as axial elements. A dynamic study of the impactor frame was made to determine how accurate a dynamic model of the frame was necessary. Strength-of-materials analysis showed
that natural frequencies of the frame and its parts could be on the same order of magnitude as those of the plates, and that careful attention needed to be paid to stiffnesses as well as masses of the frame parts. The resulting impactor mesh was therefore designed to be dynamically representative during impact.

Figure 7 illustrates the mesh developed for the I7 beam and the 8.4 lb (3.8 kg) impactor which has a 1/8-in- (3.2-mm-) radius cylindrical tip. The remaining beam meshes are similar.

B. RESULTS

Finite element analysis results were obtained for all eight plate configurations with (a) full elastic behavior, (b) flexure and transverse shear deformations only, and (c) flexure only. The longest plates, I1 and I2, with aspect ratios (length-to-thickness) of about 100, suffered numerical instability problems when both transverse shear and normal stiffnesses were artificially increased together. An attempt at resolving the problem by creating a finer mesh was thwarted by size limitations imposed by the FEAP74 code. All other runs were completed and results are available.

Runs were made at impactor initial velocities ranging from 42 in/s (500 mm/s) to 315 in/s (8 m/s). It was determined that impactor force and beam flexural strain results were proportional to velocity, and therefore only the 315 in/s (8 m/s) results are presented here.
Figure 7. Finite element mesh for 2.56 in (65 mm) x 1.57 in (40 mm) x 0.25 in (6.5 mm) graphite/epoxy plate and impactor structure.
Figure 8 illustrates the time history of axial strain which occurs at midspan on the surface of the plate on the side immediately opposite the impact location. Note that the strain is lower when transverse shear and contact deformations are included as a result of the additional energy absorption mechanisms other than flexure. Table 2 presents maximum load cell force and maximum axial strain on the surface opposite the impact point for all plates and deformation mechanisms studied. As expected, the long plates show little effect of neglecting contact and transverse shear deformations.

As previously discussed, finite element analysis was performed for the most part under an impactor velocity of 315 in/s (8 m/s) and no gravity effects. Tests, however, were carried out under velocities which varied from 19 in/s (480 mm/s) to 170 in/s (4300 mm/s). In order to compare finite element analysis results with test results, a non-dimensionalization of analytical data from finite element runs was undertaken. Using a one-degree-of-freedom system model of a mass \( m \) impacting a massless spring of spring rate \( k \) with initial velocity \( v_0 \) in a gravity field (gravitational acceleration \( g \)) gives, for the contact force \( P \) between mass and spring

\[
P = v_0(km)^{1/2}\sin(wt) + mg[1 - \cos(wt)]
\]  

where

\[
w = (k/m)^{1/2}
\]  

and \( t \) is time. If the spring is a long plate of length \( L \) clamped at either end with thickness \( h \), cross-sectional moment of inertia
Figure 8. Predicted time history of midspan axial normal strain on I7 plate surface opposite impact site.
Table 2. Maximum impactor load cell force, P, and axial bottom-surface strain, e, predicted during impact of composite plates by 8.4 lb (3.8 kg) mass at 315 in/s (8.0 m/s).

<table>
<thead>
<tr>
<th>Plate ID</th>
<th>Aspect Ratio</th>
<th>Mtl. Angle (deg)</th>
<th>Load P, kN</th>
<th>Strain e, 10^-3 m/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexure &amp; Shear</td>
<td>Flexure Only</td>
<td>Flexure &amp; Shear</td>
<td>Flexure Only</td>
</tr>
<tr>
<td></td>
<td>Deformation Modes Used</td>
<td>Deformation Modes Used</td>
<td>Deformation Modes Used</td>
<td>Deformation Modes Used</td>
</tr>
<tr>
<td>I1</td>
<td>112</td>
<td>0</td>
<td>4.35</td>
<td>4.40</td>
</tr>
<tr>
<td>I2</td>
<td>112</td>
<td>90</td>
<td>4.23</td>
<td>8.25*</td>
</tr>
<tr>
<td>I3</td>
<td>42</td>
<td>0</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>I4</td>
<td>42</td>
<td>90</td>
<td>8.16</td>
<td>8.25</td>
</tr>
<tr>
<td>I5</td>
<td>21</td>
<td>0</td>
<td>26.25</td>
<td>28.7</td>
</tr>
<tr>
<td>I6</td>
<td>21</td>
<td>90</td>
<td>20.2</td>
<td>21.2</td>
</tr>
<tr>
<td>I7</td>
<td>10</td>
<td>0</td>
<td>67.5</td>
<td>70.0</td>
</tr>
<tr>
<td>I8</td>
<td>10</td>
<td>90</td>
<td>56.0</td>
<td>56.5</td>
</tr>
</tbody>
</table>

NDG: identifies unacceptable finite element results.
*: probably incorrect due to numerical instability

I, and material plane strain extensional stiffness CXX; and if it is further assumed that the static flexural deflection curve represents dynamic deflection, then

\[ k = 192C_{XX}I/L^3 \]  \hspace{1cm} (19c)

The first term in equation (19a) is the force due to impactor initial velocity and the second term is the effect of gravity. A nondimensional load cell force \( P^{*}_{FE} \) is defined for finite element results which adds the gravitational force as follows:

\[ P^{*}_{FE} = P_{FE}/[v_0 (km)^{1/2}] + [g(km)^{1/2}/(v_0k)][1 - \cos(wt)] \]  \hspace{1cm} (20)
where \( P_{FE} \) is value of load cell force from finite element analysis at any given time \( t \). The flexural strain \( e \) in a plate undergoing dynamic impact loading represented by equations (19) is found to be

\[
e = \frac{(12h/L^3)}{\left\{ (v_0/w) \sin(\omega t) + (mg/k)(1 - \cos(\omega t)) \right\}}
\]

(21)

In a manner similar to load nondimensionalization, a nondimensional strain \( e_{*FE} \) which adds gravitational effects is defined as

\[
e_{*FE} = e_{FE}/\left[ 12v_0h/(L^2w) \right] + \left[ mgL^2w/(12v_0hk) \right][1 - \cos(\omega t)]
\]

(22)

where \( e_{FE} \) is the axial normal strain obtained from the finite element analysis. Time is nondimensionalized by the time for which a mass remains in contact with a spring for a simple mass-spring system:

\[
t^* = t/(\pi w)
\]

(23)

Nondimensional load cell force, \( P_{*FE} \), and nondimensional strain \( e_{*FE} \) opposite the impact location on the plate surface have been calculated for fully elastic finite element runs of all plates (I1 through I8). A complete set of graphs of nondimensional force and strain versus nondimensional time are presented in Appendix B.

C. COMPARISON OF FLEXURAL, CONTACT, AND SHEAR DEFORMATION EFFECTS

Table 2 presents load cell force and axial normal strain on the plate surface opposite the impact point obtained from finite element analysis with (a) all elastic deformations, (b) flexure and
transverse shear deformations but no contact deformations, and (c) flexure only with no transverse shear or contact deformations. As expected, plates with large aspect ratios (length-to-thickness) do not appear to be greatly affected by neglecting contact or transverse shear deformations. Results for plates with aspect ratios less than 40, however, show that both contact and transverse shear deformations can be important.

For quantitative comparison purposes, the data of Table 2 has been recast into Table 3 which shows the percent increase in predicted load or strain which occurs when (1) contact deformations are ignored and (2) when both contact and transverse shear deformations are ignored. Differences of three percent or less between analysis methods were not considered significant and are indicated by a dash in the table.

Table 3 shows some results which were unexpected. It was anticipated that the shorter plates (smaller aspect ratio) would show the greatest differences when contact and shear deformations were neglected. Instead, the shortest plate exhibits less difference from the fully elastic analysis than the next longer one. Time histories of the finite element results were examined, and it was found that the major reasons for the larger differences predicted in forces and strains for the longer I5 plate than for the shorter I7 plate was the superposition of higher order vibrational harmonics upon the first mode. It appears that artificially stiffening a structure by neglecting certain deformation modes can create natural frequencies which, if excited, may override the fundamental flexural deformation mode giving larger forces and strains than would ordinarily occur. This effect
Table 3. Percent increase in predicted load cell force and axial normal strain caused by neglecting contact and transverse shear deformations in elastic finite element analysis.

<table>
<thead>
<tr>
<th>Plate</th>
<th>Aspect Ratio</th>
<th>Mtl. Angle (deg)</th>
<th>Total % Increase, Load Cell Force</th>
<th>Total % Increase, Axial Normal Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deformation Mode Neglected</td>
<td>Deformation Mode Neglected</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Contact Only</td>
<td>Contact Only</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Contact Only &amp; Shear</td>
<td>Contact Only &amp; Shear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NDG</td>
<td>NDG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+95*</td>
<td>+35*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I1</td>
<td>112</td>
<td>0</td>
<td>-</td>
<td>NDG</td>
</tr>
<tr>
<td>I2</td>
<td>112</td>
<td>90</td>
<td>+95*</td>
<td>NDG</td>
</tr>
<tr>
<td>I3</td>
<td>42</td>
<td>0</td>
<td>+9</td>
<td>+20</td>
</tr>
<tr>
<td>I4</td>
<td>42</td>
<td>90</td>
<td>+9</td>
<td>+12</td>
</tr>
<tr>
<td>I5</td>
<td>21</td>
<td>0</td>
<td>+9</td>
<td>+23</td>
</tr>
<tr>
<td>I6</td>
<td>21</td>
<td>90</td>
<td>+5</td>
<td>+12</td>
</tr>
<tr>
<td>I7</td>
<td>10</td>
<td>0</td>
<td>+4</td>
<td>+9</td>
</tr>
<tr>
<td>I8</td>
<td>10</td>
<td>90</td>
<td>-</td>
<td>+17</td>
</tr>
</tbody>
</table>

- indicates less than 3% difference from complete elastic analysis.

NDG: identifies unacceptable finite element results.

* probably incorrect due to numerical instability.

Is not expected to occur for every plate since the excitation of higher order harmonics will depend upon plate stiffness (material, thickness, and length), the impactor mass and stiffness, and the initial impact velocity. Therefore, one set of impactor and velocity conditions may excite one structure and not another. This conclusion is important because it means that "rules of thumb" for deciding when to and when not to use a given analysis capability may be extremely difficult to generate since plate geometry, plate material stiffness, impactor geometry, impactor material stiffness, and impactor velocity all play a role.
However, it is clear from the data presented in Tables 2 and 3 that for AS-3501 graphite epoxy plates clamped on two opposite ends, elastic contact and transverse shear deformations play an important part in predicting accurate stresses and strains. Analyses of plates with length-to-thickness ratios greater than 40:1 do not require the inclusion of these effects to obtain accurate flexural strain predictions, while plates with 20:1 and smaller ratios will require these effects if less than 3% error is desired. It is apparent that each effect - contact and shear - accounts for anywhere between 5% and 20%, and they both appear to be equally important for the structures, materials, and impactor analyzed. It may be that these effects will be more important for plates restrained on all four sides and for spherical rather than cylindrical impactor tip geometry.

Further conclusions concerning the ability of elastic analysis to model impact of composite plates will be drawn from comparison between analysis and test results in the succeeding sections of this report.
IV. IMPACT TESTS OF AS-3501 GRAPHITE/EPOXY PLATES

A. EQUIPMENT AND TEST SETUP

1. Test Specimens

Tests were designed to duplicate the conditions of the analysis. AS-3501 graphite/epoxy laminated plates were fabricated at NAVAIRDEVCEN using two stacking sequences: 24-ply \[ ([±45/02]_2/±45/0/90)_S \] and 48-ply \[ ([±45/02]_2/±45/0/90)_{2S} \]. Specimens I1 through I4 were cut from the 24-ply laminate and specimens I5 through I8 were cut from the 48-ply laminate. Odd numbered specimens had the high-stiffness direction along the plate's longitudinal axis, while even numbered specimens had the low-stiffness direction along the plate's axis. Figure 9 gives specimen dimensions.

2. Test Apparatus

Plate impact samples were clamped at either end using one of two clamping apparatus. The shorter specimens (I3 through I8) were c-clamped between 3/8-in- (9.5-mm-) thick steel plates to a steel frame which was designed especially to fit the NAVAIRDEVCEN impact tower bed. The longest I1 and I2 plates were clamped in a modified rig normally used for plates supported on all four edges but which was modified for the two-edged support situation. The primary difference between the two clamping fixtures was the length of specimen clamped between two steel plates. Specimens I3 through I8 had clamp plates 2 in (51 mm) long on either end, while the I1 and I2 specimens were clamped 1/2 in (13 mm) on either end. Also,
Figure 9. Laminated graphite/epoxy impact test specimen geometry.
considerably greater clamping force could be exerted by the
3-clamps on the shorter specimens than could be obtained with two
eccentric 1/8 in bolts used by the rig for clamping specimens II
and III. As described below, the lesser clamping force on the II
and III specimens allowed membrane forces to pull the specimens from
the supports invalidating the tests.

Plates were impacted using the NAVAIRDEVCE instrumented impact
tower with automated data storage and reduction capabilities. The
tower, shown in Figure 10, consists of two cylindrical impactor
guides, the impactor which contains a load cell for measuring
impact force, a mechanism for drop height control/impactor lift and
automatic release, a test bed with specimen supports, and
instrumentation for measuring velocity of impactor at the point of
impact. A Nicolet two-channel digital storage scope is used to
store more than 4,000 data points per timed event.

The main body of the impactor (see upper left inset, Figure 7)
is fabricated from steel plate. It contains provisions for adding
weights to control impactor mass. For the tests conducted here, no
added weights were used, and the total impactor mass was either 8.4
lbtm (3.8 kg) with a 2,000 lb (9 kN) load cell or 9.8 lbm (4.4 kg)
with a 10,000 lb (44 kN) load cell. The impactor is designed to
use interchangeable tips. For the tests conducted here, two
special cylindrical impactor tips were designed and manufactured -
one with a 2 in (51 mm) diameter impact surface and one with a 0.25
in (6.4 mm) diameter impact surface. Both were 1.625 in (41.3 mm)
wide - slightly wider than the specimens. Nearly all of the tests
were conducted with the 2,000 lb (9 kN) load cell and the 0.25 in
(6.4 mm) impactor tip.
Figure 10. Naval Air Development Center Instrumented Impact Tower.
Data were analyzed using impact computer software and plotting routines developed especially for the NAVAIRDEVCECN instrumented impact tower facility by Mr. L. W. Gause. This software provides time plots of impact force, impactor displacement, specimen strain, and absorbed energy for the impact event, and plots of impact force and absorbed energy versus impactor displacement. It also calculates velocity at impact and maximum values of force, displacement, strain, and other quantities of interest.

B. TEST PROGRAM

Nondestructive impact tests of all eight configurations of AS-3501 graphite/epoxy plates were performed. Each test specimen was strain gaged so that time histories of axial strain at midspan on the back-surface (surface opposite the impact site) could be measured and compared with analysis. Both back-surface strain and impactor load cell force were recorded during the impact event on the Nicolet digital storage scope.

Drop heights varied between 1.0 in (25 mm) and 5.0 in (125 mm) resulting in impact velocities from about 2 ft/s (0.6 m/s) to 5 ft/s (1.5 m/s). Care was taken to maintain back-surface strain less than 0.005 to avoid structural cracks.

One specimen of each size and material orientation was subjected to three consecutive tests at the same drop height to demonstrate repeatability. Time histories of impact events were found to be nearly identical (impact loads and structural strains were virtually the same from test-to-test, varying less than 1% in magnitude and duplicating higher order harmonics as small as 0.02
of the total impact period). Due to the excellent repeatability of test data, two impact tests were deemed sufficient for each test condition: the first to measure force and strain, and the second to measure impact velocity and to verify that the specimen had not been damaged (identical traces of impact force with time were considered to show that insignificant damage had occurred).

Appendix C lists the impact tests performed on specimen configurations 11 through 18.

C. RESULTS

Contact load and back surface strain histories for each test were stored on floppy diskettes by the Nicolet storage scope. The computerized data reduction system was utilized to obtain experimental verification of impact velocities; to calculate impactor head displacement and absorbed energy; and to generate time plots of impactor force, plate axial strain, displacement, and absorbed energy.

Figures 11 through 13 show the reduced data for the 17 specimen impacted at 3.6 ft/s (1.1 m/s). Similar plots have been obtained for all specimens and a complete set is provided in Appendix D.

It is noted that the longest plates (specimens 11 and 12 with aspect ratios 100:1) pulled loose from the supports due to large deflections creating significant membrane force effects, and the data may be invalid for comparison with analytical predictions.

For comparison with the analytical predictions, load cell force, plate axial normal strain, and contact impact duration were nondimensionalized in the manner used for the analytically
Figure 11. Impactor load cell force and axial normal plate strain versus time for specimen I7, impactor velocity 3.6 ft/s (1.1 m/s).
INSTRUMENTED IMPACT TEST

Figure 12. Impactor load cell force and absorbed energy versus time for specimen 17, impactor velocity 3.6 ft/s (1.1 m/s).

-45-
INSTRUMENTED IMPACT TEST

I75LNG(ISB) 5/29/86

Force (Lbf)

2000

1600

1200

800

400

0

0.000

0.010

0.020

0.030

0.040

0.050

Absorbed energy (Ft-Lb)

5.000

4.000

3.000

2.000

1.000

0.000

Displacement (in)

MASS= 9.78Lbm
V0= 3.64Ft/sec
Eo= 2.02Ft-Lb

MAX LOAD= 1468 Lbf
Displacement= .0291 inch
E absorbed= 1.77Ft-Lb
TIME= 0.425E-04 sec

Figure 13. Impactor load cell force and absorbed energy versus impactor displacement for specimen I7, impactor velocity 3.6 ft/s (1.1 m/s).
determined quantities, but without the gravity term which is not needed for the test data:

nondimensional load cell force from test:

\[ p^*_{\text{EXP}} = P_{\text{EXP}} / \left( v_0 (\text{km})^{1/2} \right) \]  

(24)

nondimensional strain opposite impact location from test:

\[ e^*_{\text{EXP}} = e_{\text{EXP}} / \left[ 12 v_0 h / (L^2 w) \right] \]  

(25)

where \( P_{\text{EXP}} \) and \( e_{\text{EXP}} \) are test impactor force and plate strain, respectively, \( k \) is plate stiffness given by equation (19b), \( v_0 \) is impact velocity, \( m \) is impactor mass, \( h \) is plate thickness, and \( L \) is plate length between supports. [Nondimensional time \( t^* \) is given by equation (23).]

Nondimensional time histories of impactor force and plate axial normal strain are presented in Figures 14 and 15 for the I7 specimen impacted at 3.6 ft/s (1.1 m/s). Complete nondimensional results are presented in Appendix E.

Nondimensional test results are summarized with finite element results in Table 4. The first line of \( p^* \) and \( e^* \) data for each specimen are amplitudes of the first mode force and strain responses, respectively. The second line gives the maximum higher mode amplitudes. The maximum amplitude of force or strain may be found by adding first mode and higher mode amplitudes. The nondimensional contact impact duration \( t^*_{\text{MAX}} \) is the time for which the impactor remains in contact with the plate during the initial impact event nondimensionalized by equation (23). Data for the long plate I1 and I2 specimens are included for completeness even though they may be invalid as discussed above.
INSTRUMENTED IMPACT TEST

I74LNG (15B)

Figure 14. Nondimensional impactor load cell force, $p^*$, versus nondimensional time for specimen 17, impactor velocity 3.6 ft/s (1.1 m/s).
INSTRUMENTED IMPACT TEST

I74LNG(I5B)

Figure 15. Nondimensional axial normal plate strain versus nondimensional time for specimen I7, impactor velocity 3.6 ft/s (1.1 m/s).
Table 4. Nondimensional impactor force $p^*$, plate axial normal strain $e^*$, and contact impact duration $t^*$MAX obtained by finite element analyses (FE) and tests (EXP).

<table>
<thead>
<tr>
<th>SPM NO.</th>
<th>1ST MODE FORCE AND STRAIN* + HIGHER MODE RESPONSE</th>
<th>IMPACT DURATION</th>
<th>STRAIN RATIO$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1ST MODE FORCE AND STRAIN* + HIGHER MODE RESPONSE</td>
<td>IMPACT DURATION</td>
<td>STRAIN RATIO$</td>
</tr>
<tr>
<td></td>
<td>$p^*$EXP</td>
<td>$p^*$FE</td>
<td>$e^*$EXP</td>
</tr>
<tr>
<td>I1</td>
<td>112</td>
<td>0.85</td>
<td>0.90</td>
</tr>
<tr>
<td>I2</td>
<td>112</td>
<td>1.18</td>
<td>1.4</td>
</tr>
<tr>
<td>I3</td>
<td>42</td>
<td>0.65</td>
<td>0.66</td>
</tr>
<tr>
<td>I4</td>
<td>42</td>
<td>0.60</td>
<td>0.68</td>
</tr>
<tr>
<td>I5</td>
<td>21</td>
<td>0.50</td>
<td>0.58</td>
</tr>
<tr>
<td>I6</td>
<td>21</td>
<td>0.53</td>
<td>0.62</td>
</tr>
<tr>
<td>I7</td>
<td>10</td>
<td>0.38</td>
<td>0.58</td>
</tr>
<tr>
<td>I8</td>
<td>10</td>
<td>0.39</td>
<td>0.69</td>
</tr>
</tbody>
</table>

$ First mode: amplitude of fundamental frequency force and strain response.
Higher mode: amplitude of frequency response for second and higher mode frequencies combined.

Strain ratio: ratio of plate axial normal strain on the back surface obtained experimentally to that predicted by finite element analysis.

Experimental data for the long I1 and I2 plates are suspect due to support slippage during the test.

HIGH and LOW MATL STIFFNESS indicate that odd numbered specimens have approximately [±45/0₂]₅ layup and even numbered specimens have approximately [±45/90₂]₅ layup. Refer to Figure 9.
Recall that impact test results are nondimensionalized with respect to maximum values predicted by an elementary one degree of freedom strength of materials analysis: nondimensional quantities of 1.0 indicate that experimental results and one degree of freedom results coincide. As expected, test results (columns 3, 5, and 7) for the I3 through I8 specimen tests are generally closer to the one degree of freedom predictions for longer, thinner plates. It is not likely that tests should agree with the one degree of freedom predictions even for long plates, since the analysis ignores higher degree vibrational modes.

Contact and transverse shear deformations effectively add flexibility to a structure, and these effects are more important for shorter plates. Therefore, the decrease in nondimensional impactor force and plate axial normal strain with decrease in aspect ratio is expected, as is the increase in contact impact time with decrease in aspect ratio.

Except for the longest I1 and I2 specimens, the data appear to be consistent and in accord with fundamental principles.
V. COMPARISON OF IMPACT ANALYSIS WITH TESTS

Table 4 presents nondimensional impactor force, plate axial strain, and contact impact time for analytical elastic finite element results (columns 4, 6, and 8) in addition to experimentally measured values (columns 3, 5, and 7). Column 9 is the ratio of the experimentally measured plate axial normal strain to that predicted by the finite element analysis.

It is apparent from Table 4 that the small displacement elastic analysis, even with transverse shear and contact deformations, may be inadequate to predict structural strains for composite plates. Experimental strains were from 15% lower to 45% higher than predicted by the finite element elastic analysis.

The shortest plates (aspect ratio 10:1) exhibited smaller axial normal strains and impactor forces than predicted. Transverse shear and contact viscoelasticity may account for these differences. If so, the effects may be more pronounced for plates supported on all edges and for sharper impact indenter radii than the 1/8-in (3-mm) radius used for both test and analysis.

Experimental axial strains in the longer plates (aspect ratios greater than 20:1) were greater than predicted by analysis. It is doubtful that viscoelastic effects can account for this difference, since they would absorb more energy and reduce flexural strains. Membrane effects would stiffen the structure and reduce flexural strains. Although additional axial strains would be imparted by the membrane forces, it is not anticipated that they would increase total axial strains beyond those which would be predicted by small displacement flexural analysis.
VI. CONCLUSIONS

The major conclusions from this study are as follows:

1. Flexural viscoelasticity is not an important energy absorption mode during low-velocity impact of graphite/epoxy composite plates. The degree of flexural viscoelastic behavior required to fit experimental impact data of graphite/epoxy plates is several orders of magnitude larger than that available in the material.

2. Finite element analysis indicates that elastic contact and transverse shear deformations are important to accurate prediction of structural stresses and strains for plates clamped on opposing edges with length-to-thickness ratios of 20 and less. Results of purely flexural analysis of plates with aspect ratios of 40 and greater appears not to differ from results of analyses containing elastic contact and transverse shear deformation effects.

3. The neglect of contact and transverse shear effects can alter the structural response of an impacted plate by creating a higher order resonant response (or eliminating one) and may produce large errors in stress and strain predictions. It is therefore difficult to develop quantitative "rules of thumb" for errors resulting from analytical approximations, as the dynamic response will depend upon plate geometry, plate material, support conditions, impactor mass, and impactor structural geometry and stiffness. However, present analyses indicate that errors between 5% and 20% can result for short plates by neglecting either contact or shear deformations.
4. Membrane effects are definitely important for plates clamped on two opposing edges having aspect ratios of 100 or greater.

5. Comparison between analysis and test shows that elastic contact and shear deformation modeling still overpredicts strains in impacted graphite/epoxy plates with aspect ratios of 10 or less. Transverse normal and shear viscoelastic behavior might explain the difference. It is recommended that an analysis capability which includes these viscoelastic effects be developed and used to study stresses and strains in plates supported on all sides. It is probable that fully supported plates impacted with a spherical indenter will exhibit greater discrepancies than the plates used in this study which were supported on two opposing ends and impacted with a cylindrical indenter.

6. Experimental strains in long plates (aspect ratios of 20 and greater) can be as much as 48% higher than analytical elastic predictions. This might be due to two effects:
   (a) membrane forces during large deflections, and/or
   (b) significant structural natural frequency alteration due to improper material modeling.

This points to the need for inclusion of membrane force effects (e.g., references [12, 13] or [17]) in the analysis of plates, reinforces the desirability of modeling viscoelastic contact and shear behavior of the material, and shows the advisability of conducting a study which will evaluate these effects for plates supported on all edges.
7. It is well-known that the prediction of accurate deflections does not insure that stresses and strains are accurately predicted: since displacements are integrals of strains and integration is a "smoothing" process, there are many examples of analyses which may have only 3% error in displacement but as much as 20% error in strains and stresses. In a similar fashion, the existence of the well-known St. Venant effect, where self-equilibrating stress states decay rapidly with distance from the disturbance, generally indicates that high locally-generated stresses and strains will reduce rapidly with distance from the cause. Therefore, the errors in axial normal strain reported here are most likely indicative of much larger errors in stresses and strains in the immediate vicinity of the contact impact location.

8. Progress has been made to determine which analytical capabilities are necessary to accurately analyze the impact response of composite plates for design purposes. However, the program has raised new questions as well as answered old ones. Continued investigation into this problem is necessary until the answers are obtained. Only then can the composites community be satisfied that it can accurately and efficiently analyze not only structural stresses and strains (those not in the impact region and not directly affected by contact stresses), but also stresses in the immediate vicinity of the contact region.
VIII. REFERENCES


APPENDIX A. CREEP TEST DATA FOR [45] AS-3501 GRAPHITE/EPOXY LAMINATES
NOMINAL 125 lb CREEP TEST  EXPANDED TIME SCALE

\[ \varepsilon = \frac{11.17}{2.35} \times 4.46 \times 10^{-6} \times 0.01838 \]

\[ p = 5172.7 \text{ lb/} \text{in}^2 \]

\[ E_\infty = \frac{\sigma_0}{\varepsilon_\infty} = \frac{5172.7}{0.00138} = 3.745 \times 10^6 \text{ lb/} \text{in}^2 \]
125 lb CREEP TEST

\[ \Delta \sigma = \frac{27.5 \text{ psi}}{28.5 \text{ psi}} \times \frac{4 \text{ in.}}{0.01 \text{ in.}^2} = 18.65 \text{ lb/in.}^2 \]

\[ \Delta E = \frac{25.2 \text{ in.}}{24.3 \text{ in.}} \times \frac{1}{20} = 0.005 \text{ in.} \]

\[ E_x = \frac{2.5 \times 10^6 \text{ lb/in.}^2}{28.5 \times 0.005 \times 28.5} \times \frac{1}{1000} \]

\[ E_{x_{11}} = 3.402 \times 10^6 \text{ lb/in.}^2 \]

\[ E_{x_{BB'}} = 3.30 \times 10^6 \text{ lb/in.}^2 \]
1/2 in +45/-45 CREEP 250# C (NOMINAL)

GRAPHIC:

- STRAIN

- LOAD

- TIME, sec

- LOAD, V
  (50 lb/V)

- V (1000 lb/V)
STATIC TEST #1
Y2 IN SPECIMEN
1000 lbf/20 mil

LOAd
V
(50 lb/V)

LOAd/NO

STRAIN, V (1000 με/μ)

\[ E = 2.3168 \times 10^4 \]

\[ \Delta l = \frac{24.1 lb}{26.35 \times \frac{440 lb}{10 \text{mil}^2}} = 16.377 \times 10^3 \text{mil}^2 \]

\[ \Delta l = \frac{200 \text{ lb} \times 200 \times 10^6}{29.15 \text{ lb}^2} = 586.78 \times 10^6 \]

\[ E_s = 2.889 \times 10^6 \text{ lb/mil}^2 \]
STATIC TEST #2
4500 lb; BURLINGTON
26 lb; NINHAL MAX(L/N)

LOAD V
(50 lb/V)

3

2

1

0

-1

-2

-3

-4

STRAIN, V (1000 με/V)

-4 -3 -2 -1 0 1 2 3 4

LOADING

UNLOADING

\[\frac{\Delta V}{2W} \times \frac{4000}{1.21} = 17,937 \text{ V/V}\]

\[\Delta \epsilon = \frac{20,155}{29.5 \times 10} = 0.00684\]

\[E_\text{ax} = \frac{17,937}{0.00684} = 2,623,768 \text{ psi}\]

\[E_\text{ax} = 3.15 \times 10^6 \text{ psi}\]

\[\frac{\Delta V}{W} = \frac{17,937}{18,347} = 0.00684\]

\[E_\text{ax} = \frac{18,347}{0.00684} = 2,692,900 \text{ psi}\]
STATIC TEST #9
1/2 IN RAMP LOAD TO FAILURE

\[ \Delta \sigma = \frac{24,000 \text{ lb}}{28.3 \text{ in}^2} \times 0.0044 = 10 \times 30.9 \times 10^6 \text{ lb/in}^2 \]

\[ \Delta \varepsilon = \frac{20 \text{ in} \times 10^{-6}}{29.15 \text{ in}} \]

\[ E = \frac{3,007 \times 10^6 \text{ lb/in}^2}{} \]
S/N 85  T#1: 1"  [±45]  320 LB CREEP, 5 MIN

SPM 2

TIME

LOAD

STRAIN

STRAIN V (1000 µE/V)

LOAD V (200 lb/v)

-10
-7.5
-5
0
2.5
5
7.5
10

-2
-1.5
-1
-0.5
0

S MIN, 0 S

5
10
15
20
25 S

S MIN, 0 S
5/9/85 T#1: 1" [+ -45] 320 LB CREEP, 0 MIN

\[ \text{LOAD, } V (200 \text{ lb/V}) \]
5/9/85 SPM 2, T#2: 1" [+/-45] 320 LB CREEP, 0 MIN.

**Diagram Description:**
- **Axes:**
  - X-axis: Time, S (0 to 25)
  - Y-axis: Strain (0 to -4) and Load (0 to 2)
- **Graph Notations:**
  - Strain
  - Load
  - Zero Strain
  - Zero Load
- **Units:**
  - Strain: (1000/μεε/N)
  - Load: (200 lb/V)
- **Legend:**
  - MCL CREEP 1
  - TRK 7

**Observations:**
- The graph shows the strain and load over time, indicating the creep behavior of the material under load.
- The zero strain and load points are marked clearly.
- The y-axis scale is fine-tuned for detailed observation of strain and load changes.
5/9/85 SPM 2, T#2: 1" [+/-45] 320 LB CREEP, 10 MIN.

- STRAIN V (1000 μεV/V)
- -1
- -2
- -3
- -4

- LOAD V (200 lb/V)
- -0.5
- -1
- -1.5
- -2

TIME
10 MIN, 0 S 5 10 15 20 10 MIN, 25 S
5/9/85 SPM 2, T#3: 1· [±45] 320 LB CREEP, 5 MIN.

<table>
<thead>
<tr>
<th>TIME</th>
<th>LOAD V (200 lb/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MIN</td>
<td>0 (200 lb/v)</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>5 MIN, 25 s</td>
<td>0</td>
</tr>
</tbody>
</table>
5/9/85 SPM 2, T#3: 1" [±45] 320 LB CREEP, 10 MIN.

---

**Graph Details:**

- **Label:** STRAIN (100 μεV/V)
- **Axes:**
  - X-axis: TIME (0-25 MIN)
  - Y-axis: STRAIN (1, 0.5, 0, -0.5, -1, -1.5, -2, -4)

---

**Legend:**
- **Load V:** (20016V)
- **Strain:**
5/9/85 SPM 2, T#4: 1° [+45] 635 LB CREEP, 10 MIN.

- Chart shows the relationship between time and strain.
- The x-axis represents time in minutes, from 0 to 20 minutes in 5-minute intervals.
- The y-axis represents strain in milli-epsilon (με) from 0 to -4 in 1 unit increments.
- The graph indicates a steady state of strain over the 10-minute period.
5/9/85 SPM 2, T#5: 1" [+-45] 640 LB CREEP, 5 MIN.

5 MIN, 0 S

5 MIN, 5 S

5 MIN, 10 S

5 MIN, 15 S

5 MIN, 20 S

5 MIN, 25 S

STRAIN = 4.010 V (DATA OUT OF PLOTTER RANGE)

0.5

-0.5

-1

-1.5

-2

LOAD

(200lb/V)
5/9/85 SPM 2, T#5: 1° [+/-45] 640 LB CREEP, 0 MIN.

LOAD, V (200 lb/V)

STRAIN
(1000 μεε/V)

0

1

2

3

4

-1

-2

-3

-4

-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
5/9/85 SPM 3, T°1: 1° [+45] 320 LB CREEP, 5 MIN.
5/9/05 SPM 3, T#3: 1° [+/-45] STATIC RAMP TO FAIL.
5/9/85 SPM 3, T#3: 1" ± [±45] STATIC RAMP TO FAIL.

EXPANDED SCALES

-13.92

-40

TIME

233 S

-10

-54

0

1048 lb @ FAILURE

LOAD V (200 lb/v)

STRAIN V (1000 με/v)

STRAIN CASE FAILURE

LOAD

ZERO STRAIN

ZERO LOAD
5/9/85 SPM 3, T#3: 1° [+/-45] STATIC RAMP TO FAIL.

GAGE FAILURE

FAILURES LOAD: 1047 lb
APPENDIX B. NONDIMENSIONAL IMPACTOR FORCE $p^*$ AND AXIAL BACK-SURFACE STRAIN $e^*$ VS. TIME $t^*$ FROM FINITE ELEMENT ANALYSIS OF IMPACTED AS-3501 COMPOSITE PLATES
I1LIQVH and I1LIQV8

\[ V_o = 5,000 \text{ mm/s} \]

\[ V_o = 9,000 \text{ mm/s} \]
ILIQVH and ILIQV8
$V_o = 500 \text{ mm/s}$  
$V_o = 8,000 \text{ mm/s}$

Strain (dimensionless) $\times 10^{-1}$

Time (t* dimensionless) $\times 10^{-1}$
If TIM Ct Im 3 1 -B4

I2LIQVH and I2LIQV8
V₀ = 500 mm/s
V₀ = 8,000 mm/s

LOAD (p* dimensionless) × 10⁻¹

TIME (t* dimensionless) × 10⁻¹
I2LIQVH and I2LIQV8

\[ V_0 = 500 \text{ mm/s} \]

\[ V_0 = 8,000 \text{ mm/s} \]

STRAIN (ext. dimensionless) \(*10^{-1}\)

TIME (t/s dimensionless) \(*10^{-1}\)
STRAIN (t* dimensionless) x 10^-1

TIME (t* dimensionless) x 10^-1

I5LIQV8
APPENDIX C. LIST OF PLATE IMPACT TESTS, TEST CONDITIONS, AND MAGNETIC DISK STORAGE DATA
<table>
<thead>
<tr>
<th>TEST NO</th>
<th>DATA TAKEN</th>
<th>LOAD CALIB (kN/div)</th>
<th>STRAIN CALIB (V/ue)</th>
<th>DROP HEIGHT (in, mm)</th>
<th>DATA DISK MBI*</th>
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-C2-
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<th>DROP HEIGHT (in,mm)</th>
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* Data disks are labelled "McLaughlin Beam Impact (disk no.)"


*** Data for these specimens suspect due to support slippage.

Grp - Large deflections and support slippage allowed plate to be fully dislodged from grips.

Fail - Flexural failure observed in specimen.
APPENDIX D. DIMENSIONAL PLOTS OF GRAPHITE/EPOXY PLATE IMPACT TEST RESULTS
INSTRUMENTED IMPACT TEST

I71LNG(ISB) 5/29/86 12:2

Force (Lbf)

0.0E+0 1.0E-3 2.0E-3 3.0E-3 4.0E-3 5.0E-3

Time (sec)

0 1200 2000 4000 5000

Micro-Strain

MAX LOAD= 1284 Lbf
MASS= 9.78 Lbm
HEIGHT= .17 Ft

MAX STRAIN= 4195 Micro inch/inch
RADIUS= .13 inch
LOAD SCALE= .8KN/DIV
INSTRUMENTED IMPACT TEST

I73LNG(I5B) 5/29/86 12.3

MAX LOAD = 1464 Lbf
MASS = 9.78 Lbm
MAX STRAIN = 4675 Micro inch/inch
RADIUS = .13 inch
LOAD SCALE = .8KN/DIV
INSTRUMENTED IMPACT TEST

I74LNQ(I5B) 5/29/06 I2.4

Force (Lbf) vs Time (sec)

MAX LOAD = 1453 Lbf
MAX STRAIN = 4620 Micro inch/Inch
RADIUS = 0.13 inch

MASS = 9.78 Lbm
HEIGHT = 0.21 Ft
LOAD SCALE = 0.8KN/DIV
INSTRUMENTED IMPACT TEST
I75LNG(IS8) 5/29/86

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<td>4.0E-4</td>
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<td>2.0E-3</td>
<td>5.000</td>
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**Parameters:**
- **Mass:** 9.78 Lbm
- **Max Load:** 1468 Lbf
- **Time:** 8.425E-04 sec
- **Vo:** 3.64 Ft/sec
- **Displacement:** 0.0291 inch
- **Eo:** 2.02 Ft-Lb
- **E absorbed:** 1.77 Ft-Lb
INSTRUMENTED IMPACT TEST

I75LNG(ISB) 5/29/86

Mass = 9.78Lbm
V0 = 3.64ft/sec
E0 = 2.02Ft-Lb

Max Load = 1468 Lbf
Displacement = .0291 inch

E absorbed = 1.77Ft-Lb

Displacement (in)

Absorbed energy (Ft-Lb)
INSTRUMENTED IMPACT TEST
I76LNG(ISB) 5/29/86

MASS = 9.78Lbm
MAX LOAD = 2101 Lbf
TIME = 0.1250E-04 sec

Vo = 5.09Ft/sec
Displacement = .0392 inch

Eo = 3.93Ft-Lb
E absorbed = 3.42Ft-Lb
INSTRUMENTED IMPACT TEST

I78LNG(ISB) 5/29/86

MASS = 9.78 Lbm
V0 = 5.08 Ft/sec
E0 = 3.93 Ft-Lb
MAX LOAD = 2101 Lbf
Displacement = .0392 inch
E absorbed = 3.42 Ft-Lb
TIME = 8.1250E-04 sec
INSTRUMENTED IMPACT TEST

I77LNG(ISB) 5/29/86

MAX LOAD = 2100 Lbf
MASS = 9.78 Lbm
MAX STRAIN = 6440 Micro Inch/inch
RADIUS = 0.13 inch
HEIGHT = 0.42 Ft
LOAD SCALE = 0.8KN/DIV
INSTRUMENTED IMPACT TEST

NADC-871 06-60

MAX LOAD= 1131 Lbf       MASS= 9.78 Lbm       HEIGHT=  .17 Ft
MAX STRAIN=  3540 Micro Inch/Inch
RADIUS=  .13 inch       LOAD SCALE=  .8KN/DIV
INSTRUMENTED IMPACT TEST
I79LNG(I5E) 6/2/86

MASS = 8.41 Lb
Vo = 3.24 Ft/sec
Eo = 1.37 Ft-Lb
MAX LOAD = 1133 Lbf
Displacement = 0.254 inch
E absorbed = 1.21 Ft-Lb

Time (sec)
INSTRUMENTED IMPACT TEST

I79LNG(I5E) 6/2/86

Force (Lbf)

Absorbed energy (Ft-Lb)

Displacement (in)

MASS = 0.41Lbm
MAX LOAD = 1138 Lbf
TIME = 8.2250E-04 sec

Vo = 3.24Ft/sec
Displacement = 0.0254 inch

Eo = 1.37Ft-Lb
E absorbed = 1.21Ft-Lb
INSTRUMENTED IMPACT TEST

1710LG(I5E) 6/2/86

Force (Lbf) vs. Time (sec)

Absorbed Energy (ft-lb) vs. Time (sec)

MASS = 8.41Lbm
MAX LOAD = 1270 Lbf
TIME = 8.6750E-04 sec

Vo = 3.62Ft/sec
Displacement = 0.0292 inch

Eo = 1.71Ft-Lb
E absorbed = 1.57Ft-Lb
INSTRUMENTED IMPACT TEST

1710LG(15E) 6/2/86

MASS = 8.41Lbm
Vo = 3.62Ft/sec
Eo = 1.71Ft-Lb

Displacement (in)
MAX LOAD = 1270 Lbf
Displacement = 0.0292 inch
E absorbed = 1.57Ft-Lb

TIME = 0.6750E-04 sec
INSTRUMENTED IMPACT TEST

I711LG(I5E) 6/2/86

Force (Lbf) vs. Time (sec)

MAX LOAD = 1270 Lbf
MASS = 8.41 Lbm
MAX STRAIN = 3995 Micro Inch/Inch
RADIUS = 0.13 inch
HEIGHT = 0.21 Ft
LOAD SCALE = 0.8KN/DIV
INSTRUMENTED IMPACT TEST

I712LG(I5E) 6/2/86

Force (Lbf)

0.0E+0 4.0E-4 8.0E-4 1.2E-3 1.6E-3 2.0E-3

Time (sec)

Micro-Strain

0 2000 4000 6000 8000 10000

MAX LOAD= 1773 Lbf  MASS= 8.41 Lbm  HEIGHT= 0.42 Ft

MAX STRAIN= 5340 Micro inch/inch  LOAD SCALE= 0.8KN/DIV

RADIUS= 0.13 inch
INSTRUMENTED IMPACT TEST

I713LG(I5E) 6/2/86

Force (Lbf)
0 400 800 1200 1600 2000

Absorbed Energy (ft-lb)
0 1.000 2.000 3.000 4.000 5.000

Time (sec)
0.0E+0 4.0E-4 8.0E-4 1.2E-3 1.6E-3 2.0E-3

MASS= 8.41Lbm  MAX LOAD= 1782 Lbf  TIME=8.6750E-04 sec
Vo= 5.01Ft./sec  Displacement= .03961inch
Eo= 3.28Ft-Lb  E absorbed= 3.05Ft-Lb
INSTRUMENTED IMPACT TEST

I713LG(I5E) 6/2/86

Mass = 8.41 Lbm
Max Load = 1782 Lbf
Time = 8.6750E-04 sec
Vo = 5.01 Ft/sec
Displacement = .03961 inch
Eo = 3.28 Ft-Lb
E absorbed = 3.05 Ft-Lb
INSTRUMENTED IMPACT TEST

IBILNG(IGA) 6/2/86

Force (Lbf)

Absorbed Energy (ft-lb)

0.000 0.400 0.800 1.200 1.600 2.000

0.0E+0 1.0E-3 2.0E-3 3.0E-3 4.0E-3 5.0E-3

Time (sec)

MASS= 8.41Lbm MAX LOAD= 887 Lbf TIME=9.9750E-04 sec
Vo= 3.22Ft/sec Displacement=.0306inch
Eo= 1.35Ft-Lb E absorbed= 1.18Ft-Lb
INSTRUMENTED IMPACT TEST

I81LNG(I6A) 6/2/86

Force (Lbf)

Displacement (in)

Mass = 8.41 Lbm
Max Load = 887 Lbf
Time = 9.9750E-04 sec
Vel = 3.22 Ft/sec
Displacement = 0.0306 inch
E = 1.35 Ft-Lb
E Absorbed = 1.18 Ft-Lb
INSTRUMENTED IMPACT TEST

IB2LNG(16A) 6/2/86

---

**Force (Lbf)**

**Time (sec)**

- MAX LOAD = 739 Lbf
- MASS = 8.41 Lbm
- MAX STRAIN = 4855 Micro inch/inch
- RADIUS = 0.13 inch
- HEIGHT = 0.17 Ft
- LOAD SCALE = 0.8KN/DIV

---

**Micro-Strain**

---
INSTRUMENTED IMPACT TEST

I83LNG(16A) 6/3/86

MAX LOAD= 1302 Lbf
MAX STRAIN= 8400 Micro inch/inch
RADIUS= .13 inch

MASS= 8.41 Lbm
HEIGHT= .33 Ft
LOAD SCALE= .8KN/DIV
INSTRUMENTED IMPACT TEST

IB4LNG(I6A) 6/3/86

Displacement (in)

Force (Lbf)

Absorbed energy (Ft-Lb)

MASS= 8.41Lbm MAX LOAD= 1306 Lbf TIME=8.9750E-04 sec

Vo= 4.60Ft/sec Displacement= .0408inch

Eo= 2.76Ft-Lb E absorbed= 2.23Ft-Lb
INSTRUMENTED IMPACT TEST

I85LNG(16B) 6/3/86

Force (Lbf)

0.0E+0 1.0E-3 2.0E-3 3.0E-3 4.0E-3 5.0E-3

0.000 1.000 2.000 3.000 4.000 5.000

Absorbed Energy (ft-lb)

0.0 1.0 2.0 3.0 4.0 5.0

Time (sec)

MASS= 8.41Lbm
Vo= 4.54Ft/sec
Eo= 2.69Ft-Lb
MAX LOAD= 1290 Lbf
Displacement= .0427 inch
E absorbed= 2.37Ft-Lb
TIME=9.9750E-04 sec
INSTRUMENTED IMPACT TEST

I52(I5G) 6/3/86

**Graph**: The graph shows the relationship between force (Lbf) and time (sec) for an impact test. The vertical axis represents force with a range from 0 to 1000 Lbf, and the horizontal axis represents time with a range from 0 to 5.0E-3 sec.

**Data**:
- **Mass**: 6.41 Lbm
- **Max Load**: 550 Lbf
- **Time**: 1.7675E-03 sec
- **Initial Velocity (Vo)**: 3.25 Ft/sec
- **Displacement**: 0.0507 inch
- **Energy (Eo)**: 1.38 Ft-Lb
- **Energy Absorbed (E absorbed)**: 1.31 Ft-Lb
INSTRUMENTED IMPACT TEST
I52(I5G) 6/3/86

Force (Lbf)

Displacement (in)

MAX LOAD= 550 Lbf
TIME=1.7675E-03 sec

MASS= 8.41Lbm
Displacement= .0507 inch
E absorbed= 1.31Ft-Lb

Vo= 3.25Ft/sec
INSTRUMENTED IMPACT TEST
IS3(ISG) 6/3/86

Force (Lbf) vs. Time (sec)

Absorbed Energy (ft-lb)

- Mass = 8.41 Lbm
- Max Load = 720 Lbf
- Time = 1.7575E-03 sec
- Vo = 4.25 Ft/sec
- Displacement = 0.0665 inch
- Eo = 2.35 Ft-Lb
- E absorbed = 2.21 Ft-Lb
INSTRUMENTED IMPACT TEST

I53(I5G) 6/3/86

Displacement (in)  
Max Load = 720 Lbf  
Time = 1.7575E-03 sec

Mass = 0.41 Lbm  
Velocity = 4.25 Ft/sec  
E = 2.35 Ft-Lb

Absorbed energy (Ft-Lb)

Force (Lbf)
INSTRUMENTED IMPACT TEST

I61(I6C) 6/4/86

MAX LOAD = 272 Lbf
MASS = 6.41 Lbm
MAX STRAIN = 3450 Micro Inch/Inch
RADIUS = .13 Inch
HEIGHT = .08 Ft
LOAD SCALE = .8KN/DIV
INSTRUMENTED IMPACT TEST

IG1 (LOAD CHECK)

MAX LOAD = 269 Lbf
MASS = 8.41 Lbm
MAX STRAIN = 3390 Micro inch/inch
RADIUS = .13 inch
HEIGHT = .08 Ft
LOAD SCALE = .8KN/DIV
INSTRUMENTED IMPACT TEST

I62(I6C) 6/4/86

MASS= 8.41Lbm   MAX LOAD= 270 Lbf   TIME=2.3775E-03 sec
Vo= 2.24Ft/sec   Displacement= .04871inch   E absorbed= .62Ft-Lb
INSTRUMENTED IMPACT TEST

I62(I6C) 6/4/86

MASS = 8.41 Lbm
V0 = 2.24 Ft/sec
E0 = .66 Ft-Lb

MAX LOAD = 278 Lbf
Displacement = .0487 inch
E absorbed = .62 Ft-Lb

Absorbed energy (Ft-Lb)

Displacement (in)

Force (Lbf)
INSTRUMENTED IMPACT TEST

I63(I6C) 6/4/86

MASS = 8.41Lbm  MAX LOAD = 340 Lbf  TIME = 2.4025E-03 sec
Vo = 2.73Ft/sec  Displacement = 0.0594 inch
Eo = 0.97Ft-Lb  E absorbed = 0.92Ft-Lb
INSTRUMENTED IMPACT TEST

I63(I6C) 6/4/86

MASS = 8.41Lbm
Vo = 2.73Ft/sec
Eo = .97Ft-Lb

MAX LOAD = 340 Lbf
Displacement = .0594 inch
E absorbed = .92Ft-Lb

TIME = 2.4025E-03 sec
INSTRUMENTED IMPACT TEST

I64(IGC) 6/4/96

MAX LOAD= 341 Lbf
MASS= 8.41 Lbm
MAX STRAIN= 4265 Micro inch/inch
RADIUS= .13 inch
HEIGHT= .13 Ft
LOAD SCALE= .2KN/DIV
INSTRUMENTED IMPACT TEST
I65(I6C) 6/4/86

MAX LOAD= 403 Lbf
MASA= 8.41 Lbm
MAX STRAIN= 5020 Micro inch/inch
RADIUS= .13 inch
HEIGHT= .17 Ft
LOAD SCALE= .2KN/DIV
INSTRUMENTED IMPACT TEST

I66 (ISC) 6/4/86

Force (Lbf)

Absorbed Energy (ft-lb)

0.000 0.002 0.004 0.006 0.008 0.010

0.0 100.0 200.0 300.0 400.0 500.0

0.0 0.400 0.800 1.200 1.600 2.000

MASS= 8.41 Lbm
MAX LOAD= 408 Lbf
TIME= 2.3025E-03 sec

Vo= 3.24 Ft/sec
Displacement= .0695 inch

Eo= 1.37 Ft-Lb
E absorbed= 1.29 Ft-Lb
INSTRUMENTED IMPACT TEST
I66 (IGC) 6/4/86

<table>
<thead>
<tr>
<th>Force (Lbf)</th>
<th>Absorbed energy (Ft-Lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>100.0</td>
<td>0.400</td>
</tr>
<tr>
<td>200.0</td>
<td>1.200</td>
</tr>
<tr>
<td>300.0</td>
<td>1.600</td>
</tr>
<tr>
<td>400.0</td>
<td>2.000</td>
</tr>
<tr>
<td>500.0</td>
<td></td>
</tr>
</tbody>
</table>

Displacement (in)
- MAX LOAD = 408 Lbf
- TIME = 2.3825E-03 sec
- Displacement = 0.0695 inch
- E absorbed = 1.29 Ft-Lb

MASS = 8.41 Lbm
Vo = 3.24 Ft/sec
Eo = 1.37 Ft-Lb
INSTRUMENTED IMPACT TEST

I31(I1A) 6/4/86

Force (Lbf)

Absorbed Energy (ft-lb)

0.000 0.002 0.004 0.006 0.008 0.010

0.00 0.20 0.40 0.60 0.80 1.00

200.0 160.0 120.0 80.0 40.0

MASS = 8.41Lbm
Vo = 2.19Ft/sec
Eo = .63Ft-Lb

MAX LOAD = 158 Lbf
Displacement = .0953inch
E absorbed = .66Ft-Lb

TIME = 4.9300E-03 sec
INSTRUMENTED IMPACT TEST

I31(I1A) 6/4/86

Force (Lbf)

Absorbed energy (Ft-Lb)

0.0 0.02 0.04 0.06 0.08 0.10

0.0 0.2 0.4 0.6 0.8 1.0

Displacement (in)

Mass = 8.41 Lbm
Max Load = 150 Lbf
Time = 4.9300E-03 sec

Vo = 2.19 Ft/sec
Displacement = 0.0953 inch

Eo = 0.63 Ft-Lb
E absorbed = 0.68 Ft-Lb
INSTRUMENTED IMPACT TEST

I32(I1A) 6/4/86

MAX LOAD= 155 Lbf  MASS= 8.41 Lbm  HEIGHT= .08 Ft
MAX STRAIN= 3790 Micro inch/inch  LOAD SCALE= .2KN/DIV
RADIUS= .13 inch
INSTRUMENTED IMPACT TEST

I34(I1A) 6/4/86

Mass = 8.41 Lbm
Vo = 2.92 Ft/sec
Eo = 1.12 Ft-Lb

Max Load = 213 Lbf
Displacement = .1185 inch
E absorbed = 1.09 Ft-Lb

Time (sec) vs Force (Lbf) vs Absorbed Energy (ft-lbf)
INSTRUMENTED IMPACT TEST

I34(I1A) 6/4/86

 MASS= 0.41 Lbm
 Vo= 2.92 Ft/sec
 Eo= 1.12 Ft-Lb

 MAX LOAD= 213 Lbf
 Displacement= .1185 inch
 E absorbed= 1.09 Ft-Lb

TIME= 4.3900E-03 sec

Displacement (in)

Force (Lbf)

Absorbed energy (Ft-Lb)
INSTRUMENTED IMPACT TEST

I35(I1A) 6/4/86

Force (Lbf)

Absorbed Energy (ft-lb)

0.0 0.002 0.004 0.006 0.008 0.010

0.0 100.0 200.0 300.0 400.0 500.0

0.0 0.4 0.8 1.2 1.6 2.0

MASS= 8.41Lbm
Vo= 3.14Ft/sec
Eo= 1.29Ft-Lb

MAX LOAD= 235 Lbf
Displacement= .1260inch
E absorbed= 1.27Ft-Lb

TIME=4.3900E-03 sec
INSTRUMENTED IMPACT TEST

I35(I1A) 6/4/86

Force (Lbf)

Absorbed energy (Ft-Lb)

0.0 0.04 0.08 0.12 0.16 0.20

0.0 100.0 200.0 300.0 400.0 500.0

Displacement (in)

MASS= 0.41Lbm

MAX LOAD= 235 Lbf

TIME= 4.3900E-03 sec

Vo= 3.14Ft/sec

Displacement=.1260Inch

E= 1.29Ft-Lb

E absorbed= 1.27Ft-Lb
INSTRUMENTED IMPACT TEST

I36(IIA) 6/4/86

Force (Lbf)

Time (sec)

Micro-Strain

MAX LOAD = 236 Lbf
MASS = 8.41 Lbm
HEIGHT = .17 Ft

MAX STRAIN = 5540 Micro inch/inch
RADIUS = .13 inch
LOAD SCALE = .2KN/DIV
INSTRUMENTED IMPACT TEST

I41(I2A) 6/4/86

MAX LOAD= 79 Lbf
MASS= 8.41 Lbm
HEIGHT= .04 Ft
MAX STRAIN= 4865 Micro inch/inch
RADIUS= .13 inch
LOAD SCALE= .2KN/DIV
INSTRUMENTED IMPACT TEST

I42(I2A) 6/4/86

Force (Lbf)

Absorbed Energy (ft-lb)

0.000 0.004 0.008 0.012 0.016 0.020

0.0 20.0 40.0 60.0 80.0 100.0

0.00 0.10 0.20 0.30 0.40 0.50

MASS= 8.41Lbm
Vo= 1.57Ft/sec
Eo= .32Ft-Lb

MAX LOAD= 79 Lbf
Displacement= .1104 inch
E absorbed= .35Ft-Lb

TIME= 7.0700E-03 sec
INSTRUMENTED IMPACT TEST
I42(I2A) 6/4/86

Mass = 8.41 Lbm
Vo = 1.57 Ft/sec
Eo = 0.32 Ft-Lb

Displacement (in)
Max Load = 79 Lbf
Time = 7.0700E-03 sec
Displacement = 0.1104 inch
E Absorbed = 0.35 Ft-Lb
INSTRUMENTED IMPACT TEST

Absorbed Energy (ft-lb)

MAX LOAD = 117 Lbf
Displacement = .1466 Inch
E absorbed = .67 Ft-lb

FORCE (LBF)

200.0
160.0
120.0
80.0
40.0
0.0

0.008
0.012
0.016
0.020
0.024

TIME = 6.65E-03 sec

NADC-87106-60

-D56-
INSTRUMENTED IMPACT TEST

I44(I2A) 6/4/86

MAX LOAD = 113 Lbf
MAX STRAIN = 6085 Micro inch/inch

MASS = 8.41 Lbm
RADIUS = .13 inch
HEIGHT = .08 Ft
LOAD SCALE = .2KN/DIV
INSTRUMENTED IMPACT TEST

I11(I1C) 6/5/86

Max Load = 70 Lbf
Mass = 8.41 Lbm
Max Strain = 3250 Micro Inch/Inch
Radius = .13 Inch
Height = .17 Ft
Load Scale = .2KN/Div
INSTRUMENTED IMPACT TEST

II2(I1C) 6/5/86

MASS = 8.41 Lbm
Vo = 3.17 Ft/sec
Eo = 1.32 Ft-Lb

MAX LOAD = 80 Lbf
Displacement = 0.4586 inch

TIME = 1.3675E-02 sec
E absorbed = 1.22 Ft-Lb
INSTRUMENTED IMPACT TEST

I12(I1C) 6/5/86

Force (Lbf)

Absorbed energy (Ft-Lb)

Displacement (in)

MASS = 8.41Lbm  MAX LOAD = 80 Lbf  TIME = 1.3675E-02 sec

Vo = 3.17Ft/sec  Displacement = 45861inch

Eo = 1.32Ft-Lb  E absorbed = 1.22Ft-Lb
INSTRUMENTED IMPACT TEST

II3(I1C) 6/5/86

Mass = 8.41 Lbm
Vo = 4.17 Ft/sec
Eo = 2.27 Ft-Lb

Max Load = 87 Lbf
Displacement = 0.6722 inch
E absorbed = 2.40 Ft-Lb

Time (sec)
INSTRUMENTED IMPACT TEST
I13(I1C) 6/5/86

MASS = 8.41 Lbm
Vo = 4.17 Ft/sec
Eo = 2.27 Ft-Lb

MAX LOAD = 87 Lbf
Displacement = 0.6722 inch
E absorbed = 2.40 Ft-Lb

TIME = 1.6725E-02 sec

Absorbed energy (Ft-Lb)
INSTRUMENTED IMPACT TEST

MAX LOAD = 103 Lbf
MAX STRAIN = 4215 Micro Inch/Inch

FORCE (Lbf)

Max.

HEIGHT = .29 Ft

LOAD SCALE = .2KN/DIV

Mass = 8.41 Lbm

Time (Sec) = 8.41

MICRO-STRAIN

113(IIIC) 6/5/86

NADC-87106-60
INSTRUMENTED IMPACT TEST

XI 4(II C) 6/5/86

MAX LOAD = 105 Lbf
MASS = 8.41 Lbm
MAX STRAIN = 4595 Micro inch/inch
RADIUS = .13 inch
HEIGHT = .29 Ft
LOAD SCALE = .2KN/DIV
INSTRUMENTED IMPACT TEST

Absorbed energy (ft-lb)

5.000
4.000
3.000
2.000
1.000
0.000

Force (lbf)

200.0
160.0
120.0
80.0
40.0
0.0

Displacement (in)

0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000

Mass = 8.41 lbm
Vo = 4.17 ft/sec
Eo = 2.27 ft-lb

Max load = 104 Lbf
Dispacement = .6161 inch
E absorbed = 2.38 ft-lb

NC317.5

16(C2C) 6/5/86

-D67-
INSTRUMENTED IMPACT TEST
I17(I1C) 6/5/86

Force (Lbf)

200.0
160.0
120.0
80.0
40.0
0.0
0.000
0.010
0.020
0.030
0.040
0.050
Time (sec)

Absorbed Energy (ft-lb)

5.000
4.000
3.000
2.000
1.000
0.000

MASS= 8.41Lbm
MAX LOAD= 110 Lbf
TIME= 1.6775E-02 sec

Vo= 4.76Ft/sec
Displacement= .7323inch

Eo= 2.96Ft-Lb
E absorbed= 3.26Ft-Lb
INSTRUMENTED IMPACT TEST

I17(IIC) 6/5/86

Mass = 8.41 Lbm  Max Load = 110 Lbf  Time = 1.6775E-02 sec
Vo = 4.76 Ft/sec  Displacement = 0.7323 inch
Eo = 2.96 Ft-Lb  E absorbed = 3.26 Ft-Lb
INSTRUMENTED IMPACT TEST

I18(IIC) 6/5/86

MAX LOAD= 114 Lbf
MAX STRAIN= 5025 Micro inch/Inch
RADIUS= .13 inch

MSS= 8.41 Lbm
HEIGHT= .35 Ft
LOAD SCALE= .2KN/DIV
INSTRUMENTED IMPACT TEST

I19(IIC) 6/5/86

MAX LOAD= 165 Lbf
MASS= 8.41 Lbm
MAX STRAIN= 7755 Micro inch/inch
RADIUS= .13 inch
HEIGHT= 1.00 Ft
LOAD SCALE= .2KN/DIV
INSTRUMENTED IMPACT TEST

II10(IIC) 6/5/86

MAX LOAD = 170 Lbf
MASS = 0.41 Lbm
MAX STRAIN = 7500 Micro inch/inch
RADIUS = 0.13 inch
HEIGHT = 1.00 Ft
LOAD SCALE = 0.2KN/DIV
INSTRUMENTED IMPACT TEST

MAX LOAD = 223 Lbf
MAX STRAIN = 10235 Micro inch/inch
MASS = 8.41 Lbm
RADIUS = .13 inch
HEIGHT = 3.00 Ft
LOAD SCALE = .2KN/DIV

GAGE FAILURE

Force (Lbf) 0.0 0.000 0.010 0.020 0.030

Time (Sec) .010 .020 .030 .040 .050

20000 16000 12000 8000 4000 0

MICRO-STRAIN

111(I,C) 6/5/86
INSTRUMENTED IMPACT TEST

I21(I2B) 6/5/86

MAX LOAD = 50 Lbf
MAX STRAIN = 4665 Micro inch/inch
RADIUS = .13 inch

FORCE (Lbf)

TIME (sec)

50.0
40.0
30.0
20.0
10.0
0.0

0.000 0.010 0.020 0.030 0.040 0.050

5000
4000
3000
2000
1000
0

MSS = 8.41 Lbm
HEIGHT = .08 Ft
LOAD SCALE = .2KN/DIV
INSTRUMENTED IMPACT TEST
I22(I28) 6/5/86

MAX LOAD = 48 Lbf
MAX STRAIN = 4550 Micro inch/inch
MASS = 8.41 Lbm
HEIGHT = .08 Ft
RADIUS = .13 inch
LOAD SCALE = .2KN/DIV
INSTRUMENTED IMPACT TEST

I23(I2B) 6/5/86

<table>
<thead>
<tr>
<th>Force (Lbf)</th>
<th>Absorbed Energy (ft-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>5.000</td>
</tr>
<tr>
<td>40.0</td>
<td>4.000</td>
</tr>
<tr>
<td>30.0</td>
<td>3.000</td>
</tr>
<tr>
<td>20.0</td>
<td>2.000</td>
</tr>
<tr>
<td>10.0</td>
<td>1.000</td>
</tr>
<tr>
<td>0.0</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Force (Lbf)**

**Absorbed Energy (ft-lb)**

**Time (sec)**

<table>
<thead>
<tr>
<th>MASS</th>
<th>MAX LOAD</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.41Lbm</td>
<td>49 Lbf</td>
<td>2.2750E-02 sec</td>
</tr>
</tbody>
</table>

**Vo** = 2.3 Ft/sec

**Eo** = 1.45 Ft-Lb

**Displacement** = .0581 inch

**E absorbed** = 1.52 Ft-Lb
INSTRUMENTED IMPACT TEST

I23(I2B) 6/5/86

Displacement (in)  
MAX LOAD = 49 Lbf  
TIME = 2.2750E-02 sec  
Displacement = 0.8581 inch  
E absorbed = 1.52 Ft-Lb

Mass = 8.41 Lbm
Vo = 2.3 Ft/sec
Eo = 1.45 Ft-Lb

Absorbed energy (Ft-Lb)

Force (Lbf)

0.000 0.400 0.800 1.200 1.600 2.000

0.0 10.0 20.0 30.0 40.0 50.0
INSTRUMENTED IMPACT TEST
I24(I2B) 6/5/86

MASS= 8.41Lbm
Vo= 3.17Ft/sec
Eo= 1.32Ft-Lb

MAX LOAD= 68 Lbf
Displacement= .7422inch
E absorbed= 1.69Ft-Lb

TIME=2.3425E-02 sec

Graph showing force and absorbed energy over time with key parameters.
INSTRUMENTED IMPACT TEST

Absorbed energy (ft-lb)

Force (lbf)

100.0
80.0
60.0
40.0
20.0
0.0

0.000
0.200
0.400
0.600
0.800
1.000

1.000
1.200
1.600
2.000

Displacement (in)

MAX Load = 68 Lbf
Displacement = .7422 inch
E absorbed = 1.69 Ft-lb

MASS = 8.41 Lbm
V0 = 3.17 Ft/sec
E0 = 1.32 Ft-lb

- D79 -
INSTRUMENTED IMPACT TEST

I25(J2B) 6/5/86

MAX LOAD = 71 Lbf
MASS = 8.41 Lbm
MAX STRAIN = 5805 Micro inch/inch
RADIUS = .13 inch
HEIGHT = .17 Ft
LOAD SCALE = .2KN/DIV
INSTRUMENTED IMPACT TEST

I26(I2B) 6/5/86

MAX LOAD = 87 Lbf
MASS = 8.41 Lbm
MAX STRAIN = 7850 Micro Inch/Inch
RADIUS = .13 inch
HEIGHT = .33 Ft
LOAD SCALE = .2KN/DIV
INSTRUMENTED IMPACT TEST

I27(I2B) 6/5/86

Force (Lbf)

Absorbed Energy (ft-lb)

0.000 0.010 0.020 0.030 0.040 0.050

0.0 40.0 80.0 120.0 160.0 200.0

0.000 1.000 2.000 3.000 4.000 5.000

MASS = 8.41Lbm
Vo = 4.76Ft/sec
Eo = 2.96Ft-Lb

MAX LOAD = 102 Lbf
Displacement = 1.0491 inch
E absorbed = 3.50Ft-Lb

TIME = 2.3225E-02 sec
INSTRUMENTED IMPACT TEST
I27(I2B) 6/5/86

- Mass = 8.41 Lbm
- Vo = 4.76 Ft/sec
- Eo = 2.96 Ft-Lb

Maximum Load = 102 Lbf
Displacement = 1.049 inch
Energy absorbed = 3.50 Ft-Lb
INSTRUMENTED IMPACT TEST

I28(I2B) 6/5/86

MAX LOAD = 150 Lbf
MASS = 8.41 Lbm
HEIGHT = 1.00 Ft
MAX STRAIN = 10235 Micro inch/inch
RADIUS = .13 inch
LOAD SCALE = .2KN/DIV
APPENDIX E. NONDIMENSIONAL PLOTS OF IMPACTOR FORCE $p^*$ AND PLATE AXIAL NORMAL STRAIN $e^*$ VERSUS TIME $t^*$ DURING GRAPHITE, EPXY PLATE IMPACT TESTS
INSTRUMENTED IMPACT TEST

I71LNG(I5B)

\[ P^* \]

\[ t^* \]

\[ V_0 = 3.28 \text{ Ft/s (898.7 mm/s)} \]
\[ Z = 0.823 \text{ Ft (7.9 mm)} \]
\[ p_* \text{ max} = 3.8927E-01 \]

\[ H = 0.78 \text{ Lbm (4.437E-3 Kg)} \]
\[ b = 0.131 \text{ Ft (40.8 mm)} \]
\[ a_* \text{ max} = 7.746E-01 \]

\[ L = 0.213 \text{ Ft (64.9 mm)} \]
\[ Q = 14700E+5 \text{ Lb/Ft}^2 (7.846E+4 \text{ MPa}) \]
\[ t^* \text{ max} = 2.118E+00 \]
INSTRUMENTED IMPACT TEST

I71LNG(I5B)

V = 3.28 Ft/s (899.7 mm/s)
Z = 0.823 Ft (7.8 mm)
\( p^* \) max = 3.9827E-01

M = 9.78 Lbm (4.437E-3 Mg)
b = 0.01 Ft (48.8 mm)
\( e^* \) max = 7.7486E-01

L = 0.213 Ft (64.9 mm)
Q = 14780E+6 Lb/Ft\(^2\) (7.636E+4 MPa)
\( t^* \) max = 2.1191E+00
INSTRUMENTED IMPACT TEST

I74LNG(15B)

**Graphical Data**

- **t**: Time
- **v**: Velocity
- **M**: Moment
- **L**: Length

**Variables**

- **V_0**: 3.64 Ft/s (110.5 mm/s)
- **z**: 0.023 Ft (7.9 mm)
- **p**: max = 3.883E-01
- **h**: max = 7.441E-01
- **N**: 9.70 Lbs (4.37E-3 Kg)
- **b**: 0.131 Ft (48.9 mm)
- **q**: max = 1.47E+04 Lb/Ft^2 (7.83E+3 MPa)
- **L**: 0.213 Ft (64.9 mm)
- **G**: 14700E+5 Lb/Ft^2 (7.83E+3 MPa)
- **t**: max = 2.242E+00
INSTRUMENTED IMPACT TEST
I74LNG(I5B)

V0= 3.64 Ft/s (1109.5 mm/s)
Z= 0.023 Ft (7.0 mm)
ρ# max=3.68E-01

W= 9.78 Lbm (4.437E-3 Kg)
b= .131 Ft (40.0 mm)
e# max=7.44E-01

L= .213 Ft (64.9 mm)
Q=14708E+5 Lb/Ft^2 (7.638E4 Pa)
t# max=2.24E+08
INSTRUMENTED IMPACT TEST

I74LNG(I5B)

\[ P \times t \]

\[ V_0 = 3.64 \text{ Ft/s (1189.5 mm/s)} \]
\[ L = 9.70 \text{ Lbs (4.437E-3 Mm)} \]
\[ B = 0.023 \text{ Ft (7.8 mm)} \]
\[ b = 0.131 \text{ Ft (49.9 mm)} \]
\[ Q = 14700E+5 \text{ Lb/Ft}^2 (7.83E+4 \text{ MPa}) \]
\[ P_{\text{max}} = 3.693E-01 \]
\[ a_{\text{max}} = 7.4489E-01 \]
\[ t_{\text{max}} = 2.2426E+00 \]
INSTRUMENTED IMPACT TEST

I74LNG(I5B)

V0 = 3.84 Ft/s (1188.5 mm/s)
Z = .923 Ft (7.5 mm)
p = max = 3.6936E-01

M = 8.58 Lb-m (4.437E-3 Mg)
b = .131 Ft (40.8 mm)
s = max = 7.4499E-01

L = .213 Ft (64.9 mm)
Q = 14700E+5 Lbs/ft2 (7.838E4 MPa)
t = max = 2.2426E+00
INSTRUMENTED IMPACT TEST

I77LNG(I5B)

\[
\begin{align*}
V &= 5.89 \text{ Ft/s (1551.4 mm/s)} \\
Z &= 0.623 \text{ Ft (7.8 mm)} \\
\rho \# \text{ max} &= 3.0316 \times 10^{-5} \\
\omega \# \text{ max} &= 7.4254 \times 10^{-1} \\
\tau \# \text{ max} &= 2.168E+88 \\
\end{align*}
\]
INSTRUMENTED IMPACT TEST

I77LNG(ISB)

\[ t^* \]

\begin{align*}
V_0 &= 5.09 \text{ Ft/s (1551.4 mm/s)} \\
Z &= .023 \text{ Ft (7.0 mm)} \\
p &= 3.8916E-01 \\
H &= 9.78 \text{ Lbm (4.437E 3 Kg)} \\
b &= .131 \text{ Ft (40.8 mm)} \\
o &= 7.4284E-01 \\
L &= .213 \text{ Ft (64.9 mm)} \\
Q &= 14700E+5 \text{ Lb/Ft}^2 \quad (7.038E+4 \text{ Hz}) \\
t^* &= 2.1868E+00
\end{align*}
INSTRUMENTED IMPACT TEST

I78LNG(IS6)

VB = 3.24 Ft/s (987.6 mm/s)
Z = .823 Ft (7.8 mm)
\( p^2 \) max = 3.2385E-01

\( M = 9.78 \) Lbm (4.437E-3 Mg)
\( b = .131 \) Ft (48.8 mm)
\( \omega \) max = 6.4131E-01

\( L = .213 \) Ft (64.9 mm)
\( Q = 14700E+5 \) Lb/Ft^2 (7.638E+4 MPa)
\( t^* \) max = 2.9764E+00
INSTRUMENTED IMPACT TEST

I78LNG(I5E)

**Variables and Calculations:**

- \( v_0 = 3.24 \text{ Ft/s (987.6 mm/s)} \)
- \( M = 9.78 \text{ Lbs (4.437E-3 Mg)} \)
- \( L = 0.213 \text{ Ft (64.9 mm)} \)
- \( Z = 0.023 \text{ Ft (7.8 mm)} \)
- \( b = 0.131 \text{ Ft (48.0 mm)} \)
- \( q = 147000 \text{ Lb/Ft}^2 \) (7.038E+4 MPa)
- \( \rho \) \( \text{max} = 3.2305E-01 \)
- \( e \) \( \text{max} = 6.4131E-01 \)
- \( t \) \( \text{max} = 2.8704E+08 \)
INSTRUMENTED IMPACT TEST

I711LG(I5E)

\[
\begin{align*}
V_0 &= 3.62 \text{ Ft/s (1183.4 mm/s)} \\
L &= .213 \text{ Ft (54.9 mm)} \\
T &= .023 \text{ Ft (7.8 mm)} \\
\rho \text{ max} &= 3.4897E-01 \\
\rho \text{ max} &= 6.8854E-01 \\
\rho \text{ max} &= 14700E+5 \text{ Lb/Ft}^2 (7.836E+4 \text{ MPa}) \\
\rho \text{ max} &= 2.223E+00
\end{align*}
\]
INSTRUMENTED IMPACT TEST

I711LG(I5E)

VE = 3.52 Ft/s (1183.4 mm/s)
Z = .023 Ft (7.0 mm)
p = max=+3.4987E-01

H = .41 Lbs (3.816E-3 Mg)
b = .131 Ft (40.0 mm)

Q = 14700E+5 Lb/Ft^2 (7.838E+4 MPa)
t# max=+2.2238E+00

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INSTRUMENTED IMPACT TEST

I712LG(I5E)

V0 = 5.01 Ft/s (1527.0 mm/s)
Z = .623 Ft (7.9 mm)
p# max = 9.5318E-01

M = .81 Lbm (3.818E-3 Kg)
b = .131 Ft (40.9 mm)
q# max = 8.7466E-01

L = .213 Ft (64.9 mm)
Q = 147900E+5 Lb/ Ft² (7.83E+4 MPa)
t# max = 2.1741E+00
INSTRUMENTED IMPACT TEST

I712LG(I5E)

VA= 5.81 Ft/s (1527.8 mm/s)
Z= .023 Ft ( 7.0 mm)
p# max=-9.5318E-81

V= 8.41 Lbs (3.616E-3 N)
N= .131 Ft ( 40.0 mm)
e# max=+8.7466E-81

L= .213 Ft ( 64.9 mm)
Q=14700E+5 Lbs/Ft^2 (7.038E+4 MPa)
t# max=+2.1741E+88
INSTRUMENTED IMPACT TEST

I82LNG(I6A)

V0 = 3.22 Ft/s (981.5 mm/s)
Z = .023 Ft ( 7.8 mm)
p# max =+3.2069E-01

M = 8.41 Lbm (3.016E-3 Mg)
b = .131 Ft ( 40.0 mm)
q# max =+5.6513E-01

L = .213 Ft ( 64.9 mm)
Q = 71408E+4 Lb/Ft^-2 (3.419E+4 MPa)
t# max =+1.8940E+00
INSTRUMENTED IMPACT TEST

I82LNG(16A)

VB = 3.22 Ft/s (981.5 mm/s)
Z = 0.623 Ft (7.9 mm)
W = max = +3.2E-01

M = 0.41 Lbs (3.616E-3 Mg)
b = 0.131 Ft (40.9 mm)
E max = +8.51E-01

L = 0.213 Ft (64.9 mm)
Q = 71490E-4 Lb/Ft^2 (3.421E-3 MPa)
t max = +1.894E+00
INSTRUMENTED IMPACT TEST

I03LNG(I6A)

\[ V_0 = 4.69 \text{ Ft/s} \quad (142.1 \text{ mm/s}) \]
\[ H = 0.41 \text{ Lbm} \quad (3.816E-3 \text{ Mg}) \]
\[ L = 0.213 \text{ Ft} \quad (64.9 \text{ mm}) \]
\[ Z = 0.823 \text{ Ft} \quad (248.8 \text{ mm}) \]
\[ b = 0.131 \text{ Ft} \quad (40.8 \text{ mm}) \]
\[ q \text{ max} = 71480E+4 \text{ Lb/Ft}^2 \quad (3.419E+4 \text{ MPa}) \]
\[ t \text{ max} = 1.8542E+08 \]
INSTRUMENTED IMPACT TEST

IB3LNG(ISA)

\[ t \times \]

- $V_0 = 4.68 \text{ Ft/s (1402.1 mm/s)}$
- $H = 0.41 \text{ Lbm (3.816E-3 Mg)}$
- $L = 213 \text{ Ft (64.9 mm)}$
- $Q = 71400 \text{ E-4 Lb/Ft} \times 2 \text{ (3.419E+4 MPa)}$
- $p \times \text{ max} = 4.0325E-01$
- $a \times \text{ max} = 0.1322E-01$
- $t \times \text{ max} = 1.8642E+00$
INSTRUMENTED IMPACT TEST
I86LNG(I6B)

$\rho \times \chi$

$0.000 \quad 0.400 \quad 0.800 \quad 1.200 \quad 1.600 \quad 2.000$

$t\times$

$\rho=4.54 \text{ Ft/s (1383.8 mm/s)}$
$z=0.023 \text{ Ft (7.0 mm)}$
$p\# \text{ max}=3.8849E-91$

$H=6.41 \text{ Lbs (3.816E-3 Kg)}$
$b=0.131 \text{ Ft (48.9 mm)}$
$a\# \text{ max}=7.5156E-91$

$L=0.213 \text{ Ft (64.9 mm)}$
$q=71400E+4 \text{ Lb/Ft}^2 (3.419E+4 \text{ MPa})$
$t\# \text{ max}=1.8472E+88$
INSTRUMENTED IMPACT TEST

I51(I5G)

\[ V_0 = 3.25 \text{ Ft/s (998.6 mm/s)} \]
\[ I = 0.41 \text{ Lbs (3.616E-3 Hg)} \]
\[ L = 0.443 \text{ Ft (135.8 mm)} \]
\[ Z = 0.023 \text{ Ft (7.9 mm)} \]
\[ b = 0.131 \text{ Ft (40.0 mm)} \]
\[ Q = 147000 \text{ Lb/Ft}^2 (7.838E+4 \text{ MPa}) \]
\[ t# \text{ max} = 1.4416E+00 \]
\[ p# \text{ max} = 5.8348E-01 \]
\[ e# \text{ max} = 8.6586E-01 \]
INSTRUMENTED IMPACT TEST

IS1(ISG)

V0= 3.25 Ft/s (998.8 mm/sec)
Z= .322 Ft (78.8 mm)
p# max=8.0346E-01

H= 8.41 Lbm (3.816E-3 Mg)
b= .131 Ft (40.0 mm)
\( \sigma _{\text{max}} = 8.5689E-01 \)

L= .443 Ft (135.0 mm)
Q=14788E+5 Lb/Ft^2 (7.838E+4 MPa)
\( \tau _{\text{max}} = 1.4416E+00 \)
INSTRUMENTED IMPACT TEST

I$54$($I_5G$)

$V_0 = 4.25$ Ft/s ($1295.4$ mm/s)

$Z = 0.023$ Ft ($7.6$ mm)

$p_r_{max} = 9.8382E-01$

$H = 0.41$ Lbm ($3.816E-3$ hgf)

$k = 0.131$ Ft ($40.0$ mm)

$a_{max} = 6.6344E-01$

$L = 0.443$ Ft ($135.0$ mm)

$Q = 14788E+5$ Lb/Ft$^2$ ($7.836E+4$ MPa)

$t_{max} = 1.4477E+08$
INSTRUMENTED IMPACT TEST

I54(I5G)

\( V_b = 4.25 \text{ Ft/s} \) (1295.4 mm/s)
\( Z = 0.023 \text{ Ft} \) (7.8 mm)
\( p = \max = 5.8962E-01 \)

\( N = 0.41 \text{ Lbm} \) (3.816E-3 Mg)
\( b = 0.131 \text{ Ft} \) (40.0 mm)
\( e = \max = 8.6344E-01 \)

\( L = 0.443 \text{ Ft} \) (135.0 mm)
\( Q = 14700E+5 \text{ Lb/Ft}^2 \) (7.038E+4 MPa)
\( t_\# = \max = 1.4477E+88 \)
INSTRUMENTED IMPACT TEST

I61 (I6C)

VD = 2.24 Ft/s (682.8 mm/s)
Z = 0.023 Ft (7.8 mm)
\( p' \) max = 4.213E-01

\( \phi \) = 9.41 Lbs (3.816E-3 Mg)
b = 0.131 Ft (40.9 mm)
\( e' \) max = 8.798E-01

L = 0.443 Ft (135.8 mm)
\( q = 71400E+4 \) Lb/Ft^2 (3.419E+4 MPa)
\( th \) max = 1.4346E+00
INSTRUMENTED IMPACT TEST

I61(I6C)

\[ V_B = 2.24 \text{ Ft/s (602.0 mm/s)} \]
\[ Z = 0.023 \text{ Ft (7.9 mm)} \]
\[ p_{\text{max}} = +5.2138E-01 \]
\[ t* \]

\[ M = 0.441 \text{ lbs (3.016E-3 kg)} \]
\[ b = 0.131 \text{ Ft (40.0 mm)} \]
\[ e_{\text{max}} = 0.7994E-01 \]

\[ L = 0.443 \text{ Ft (135.0 mm)} \]
\[ Q = 71400E+4 \text{ Lb/Ft}^2 (3.419E+4 \text{ MPa}) \]
\[ t*_{\text{max}} = 1.4345E+08 \]
INSTRUMENTED IMPACT TEST

I64(I6C)

$V_0 = 2.73 \text{ ft/s (83.1 mm/s)}$

$Z = 0.023 \text{ ft (7.0 mm)}$

$P_\text{max} = 5.3608E-01$

$M = 0.41 \text{ lbm (3.816E-3 kg)}$

$b = 0.131 \text{ ft (49.9 mm)}$

$\alpha \text{ max} = 0.8388E-01$

$L = 0.443 \text{ ft (135.8 mm)}$

$Q = 71480\text{E+4 Lb/Ft}^2 (3.419E+4 \text{ MPa})$

$t^\# \text{ max} = 1.4250E+00$
INSTRUMENTED IMPACT TEST
I65(I6C)

\[ V_0 = 3.24 \text{ Ft/s (987.6 mm/s)} \]
\[ Z = 0.023 \text{ Ft (7.9 mm)} \]
\[ P_{\text{max}} = 5.3333 \times 10^{-1} \]

\[ \rho \] = 0.41 Lbm (3.816E-3 Kg)
\[ b = 0.131 \text{ Ft (40.0 mm)} \]
\[ P_{\text{max}} = 0.0559 \times 10^{-1} \]

\[ t \times \] = 0.443 Ft (135.8 mm)
\[ Q = 71400 \times 10^3 \text{ Lb/ft}^2 (3.419E+4 \text{ MPa}) \]
\[ t_{\text{max}} = 1.4259 \times 10^{00} \]
INSTRUMENTED IMPACT TEST

I65(I6C)

VO = 3.24 Ft/s (987.6 mm/s)
Z = 0.829 Ft (7.8 mm)
pH max = 5.3399E-01

H = 8.41 Lbs (3.016E-3 Mg)
b = 0.131 Ft (49.0 mm)
eH max = 9.6559E-01

L = 0.443 Ft (135.0 mm)
G = 7.14 E08 Lb/Ft^2 (3.415E4 MPa)
t* max = 1.4290E+08
INSTRUMENTED IMPACT TEST

I32(IIA)

\[ \begin{align*}
V_0 &= 2.19 \text{ Ft/s (667.5 mm/s)} \\
Z &= 0.018 \text{ Ft (3.2 mm)} \\
\rho* \text{ max} &= 6.96E-01 \\
H &= 0.41 \text{ Lbs (3.81E-3 Kg)} \\
B &= 0.131 \text{ Ft (49.9 mm)} \\
\eta* \text{ max} &= 1.11E+00 \\
L &= 0.443 \text{ Ft (135.8 mm)} \\
Q &= 16280E+5 \text{ Lb/Ft}^2 (7.757E+4 \text{ MPa}) \\
t* \text{ max} &= 1.2134E+00
\end{align*} \]
INSTRUMENTED IMPACT TEST

I32(I1A)

\[ V_0 = 2.19 \text{ Ft/s (687.5 mm/s)} \]
\[ Z = 0.10 \text{ Ft (30 mm)} \]
\[ \rho' \text{ max} = 6.36E3 \text{E-01} \]

\[ N = 0.41 \text{ Lbm (3.016E-3 Mg)} \]
\[ b = 0.131 \text{ Ft (40.0 mm)} \]
\[ a' \text{ max} = 1.162E+00 \]

\[ L = 0.443 \text{ Ft (135.0 mm)} \]
\[ 0 = 18280E+5 \text{ Lb/Ft}^2 (7.757E+4 \text{ MPa}) \]
\[ t' \text{ max} = 1.2134E+00 \]
INSTRUMENTED IMPACT TEST

I33(I1A)

Vb = 2.32 Ft/s (688.6 mm/s)
Z = .810 Ft (3.2 n)
p# max = +6.0710E-01

M = 0.41 Lbs (3.616E-3 Mg)
b = .191 Ft (48.9 n)
a# max = +1.8223E+00

L = .443 Ft (135.8 n)
Q = 16288E+5 Lb/Ft-2 (7.75 kPa)
t# max = +1.2903E+00
INSTRUMENTED IMPACT TEST

I33(I1A)

VB = 2.02 Ft/s ( 000.3 mm/s)
Z = .018 Ft ( 3.2 mm)

Gmax = 46.6716E-01

H = 0.41 Lbm (3.016E-3 Mg)
b = .131 Ft ( 40.0 mm)

Nmax = 1.8223E+00

L = .443 Ft (135.0 mm)
O = 16200E+3 Lb/Ft-2 (7.757E+4 N/m²)

T max = 1.2003E+00
INSTRUMENTED IMPACT TEST

I36(I1A)

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\[ V_0 = 3.14 \text{ Ft/s (957.1 mm/s)} \]
\[ Z = 0.01 \text{ Ft (3.2 mm)} \]
\[ p_r \text{ max} = 9.9814E-01 \]

\[ H = 6.41 \text{ Lbs (3.016E-3 Mg)} \]
\[ b = 0.131 \text{ Ft (40.9 mm)} \]
\[ e \text{ max} = 1.149E+00 \]

\[ L = 0.443 \text{ Ft (135.8 mm)} \]
\[ Q = 0.16200E+5 \text{ Lb/Ft}^2 (7.757E+4 \text{ MPa}) \]
\[ t \text{ max} = 1.216E+1 \]
INSTRUMENTED IMPACT TEST

I41(I2A)

\[ P^* \]

\[ t^* \]

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\[ 1.000 \]

\[ 0.800 \]

\[ 0.600 \]

\[ 0.400 \]

\[ 0.200 \]

\[ 0.000 \]

\[ 0.000 \]

\[ 0.400 \]

\[ 0.800 \]

\[ 1.200 \]

\[ 1.600 \]

\[ 2.000 \]

\[ \text{t}^* \]

\[ V_0 = 1.57 \text{ ft/s} \ (478.5 \text{ mm/s}) \]

\[ H = 0.41 \text{ lb} \ (3.016 \text{ E-3 \ atm}) \]

\[ L = 0.443 \text{ ft} \ (135.8 \text{ mm}) \]

\[ Z = 0.818 \text{ ft} \ (3.2 \text{ mm}) \]

\[ b = 0.131 \text{ ft} \ (40.9 \text{ mm}) \]

\[ Q = 78500 \text{ E+4 Lb/Ft}^2 \ (3.753 \text{ E+4 MPa}) \]

\[ p^*_{\text{max}} \approx 6.734 \text{ E-61} \]

\[ a^*_{\text{max}} \approx 1.3937 \text{ E+88} \]

\[ t^*_{\text{max}} \approx 1.2687 \text{ E+88} \]
INSTRUMENTED IMPACT TEST
I44(I2A)

\[ V_0 = 2.25 \text{ Ft/s (685.8 mm/s)} \]  \[ M = 0.41 \text{ Lbs (1.81E-3 Mg)} \]  \[ L = .443 \text{ Ft (135.0 mm)} \]

\[ Z = .810 \text{ Ft (2.46 cm)} \]  \[ h = .131 \text{ Ft (40.0 mm)} \]  \[ \rho = 765000 \text{ Lb/ft}^2 (3.75E+4 \text{ MPa}) \]

\[ a_\# \text{ max} = -1.2184E+00 \]  \[ t \# \text{ max} = 1.2242E+00 \]
INSTRUMENTED IMPACT TEST

I44(I2A)

$V_0 = 2.25 \text{ Ft/s (685.0 mm/s)}$

$Z = 0.018 \text{ Ft (3.2 mm)}$

$p#_{\text{max}} = 6.7278E-01$

$M = 0.41 \text{ Lbm (9.016E-3 Mg)}$

$b = 0.131 \text{ Ft (40.0 mm)}$

$q#_{\text{max}} = 1.2184E+00$

$L = 0.443 \text{ Ft (135.0 mm)}$

$Q = 78500E+4 \text{ Lb/Ft}\cdot\text{sec (3.758E+4 MPa)}$

$t#_{\text{max}} = 1.2242E+00$
INSTRUMENTED IMPACT TEST

I11(I1C)

\[ V_0 = 3.17 \text{ Ft/s (966.2 mm/s)} \]
\[ Z = 0.018 \text{ Ft (3.2 mm)} \]
\[ p# \max =+8.71955E-01 \]

\[ H = 0.41 \text{ Lbm (3.016E-3 Hg)} \]
\[ b = 0.131 \text{ Ft (40.8 mm)} \]
\[ a# \max =+1.9742E+00 \]

\[ L=1.165 \text{ Ft (355.1 mm)} \]
\[ Q=16200E+5 \text{ Lb/Ft}^2 (7.757E+4 \text{ MPa}) \]
\[ t# \max =+1.1446E+00 \]
INSTRUMENTED IMPACT TEST

II4(IIc)

V0 = 4.17 Ft/s (1271.8 mm/s)
Z = .018 Ft (3.2 mm)
pmax = +0.0350E-01

H = 0.41 Lbm (3.816E-3 Mj)
b = .131 Ft (40.9 mm)
e= max = +1.0991E+00

L = 1.165 Ft (355.1 mm)
Q = 16200E+5 Lb/Ft² (7.75/E+4 MPa)
t# max = +1.1031E+00
INSTRUMENTED IMPACT TEST

IlB(IlC)

$V_B = 4.78 \text{ Ft/s} (1458.8 \text{ mm/s})$

$Z = .018 \text{ Ft} (\text{ 3.2 mm})$

$p_h \max = +9.4763E-01$

$H = 0.41 \text{ Lbm (3.016E+3 Kg)}$

$b = .131 \text{ Ft} (\text{ 48.8 mm})$

$e_h \max = +1.1061E+00$

$L = 1.165 \text{ Ft} (\text{ 355.1 mm})$

$q = 16200E+5 \text{ Lb/ft}^2 (7.757E+4 \text{ MPa})$

$t_h \max = +1.0524E+00$
INSTRUMENTED IMPACT TEST

I10(I1C)

- E47 -

\[ V_0 = 4.76 \text{ Ft/s (1458.8 mm/s)} \]
\[ Z = 0.41 \text{ Lbs (38.16E-3 Nm)} \]
\[ h = 0.13 \text{ Ft (48.9 mm)} \]
\[ \rho \text{ max} = 8.4763E-8 \]
\[ \alpha \text{ max} = 1.1961E+98 \]
\[ Q = 102E+5 \text{ Lbs/Ft}^2 (7.757E+4 \text{ MPa}) \]
\[ t_\# \text{ max} = 1.8524E+88 \]
INSTRUMENTED IMPACT TEST
I21(I2B)

\[ \text{Data:} \]

- \( V_0 = 2.30 \text{ Ft/s} \) (781.8 mm/s)
- \( Z = 0.010 \text{ Ft} \) (3.2 mm)
- \( h = 0.181 \text{ Ft} \) (46.0 mm)
- \( p_{\text{max}} = 1.2363 \text{E+00} \)
- \( a_{\text{max}} = 1.4794 \text{E+00} \)
- \( L = 1.165 \text{ Ft} \) (355.1 mm)
- \( Q = 785000 \text{ E+4} \text{ Lb/ft}^2 \) (3.759 E+4 MPa)
- \( t_{\text{max}} = 1.0568 \text{E+00} \)
INSTRUMENTED IMPACT TEST

I21(I2B)

V0= 2.38 Ft/s (781.0 mm/s)  
Z= .818 Ft ( 3.2 mm)  
\( p\#_{\text{max}} = 1.2383 \times 10^8 \)  

H= 8.41 Lbs (3.616E-3 Kg)  
b= .131 Ft ( 48.0 mm)  
\( e\#_{\text{max}} = 1.4794 \times 10^8 \)  

L=1.185 Ft (355.1 mm)  
Q=78580E+4 Lb/Ft-2 (3.795E+4 MPa)  
\( t\#_{\text{max}} = 1.0588 \times 10^8 \)
INSTRUMENTED IMPACT TEST
I25(I2B)

V0 = 3.17 Ft/s (966.2 mm/s)
Z = 0.010 Ft (3.2 mm)
p# max = 1.275E+00

M = 8.41 Lbm (3.016E-3 Kg)
b = 0.131 Ft (40.0 mm)
a# max = 1.3357E+00

L = 1.165 Ft (355.1 mm)
Q = 76500E+4 Lb/Ft^2 (3.755E+4 MPa)
t# max = 8.5773E-01
INSTRUMENTED IMPACT TEST
I25(I2B)

Vb = 3.17 Ft/s (966.2 mm/s)
Ze = .010 Ft (3.2 mm)
max= 1.3357E+00

M = 4.14 Lbs (3.016E+03 Mg)
b = .131 Ft (40.0 mm)
max= 1.5357E+00

L = 1.185 Ft (355.1 mm)
Q = 70550E+4 Lb/Ft^2 (3.753E+4 MPa)
max= 8.5773E-01
INSTRUMENTED IMPACT TEST

I26(I2B)

$V_0 = 4.76 \text{ Ft/s (1458.0 mm/s)}$

$H = 0.41 \text{ Lbs (3.816E-3 Mg)}$

$L = 1.165 \text{ Ft (355.1 mm)}$

$Z = 0.918 \text{ Ft (33.2 mm)}$

$q = 0.131 \text{ Ft (49.0 mm)}$

$Q = 78500 \text{ Lb/ft}^2 (3.755E+4 \text{ MPa})$

$p = \text{ max}=+1.9656E+00$

$s = \text{ max}=+1.2828E+00$

$t = \text{ max}=+7.7658E-01$
INSTRUMENTED IMPACT TEST

I26(I28)

Vb = 4.76 Ft/s (1450.8 mm/s)
Z = .818 Ft (3.2 mm)

H = 6.41 Lbm (3.016E-3 Mg)
b = .131 Ft (48.9 mm)

Wmax = +1.0656E+00
Wmax = +1.2629E+00

L = 1.165 Ft (355.1 mm)
Q = 78500E+4 Lb/Ft² (3.759E+4 MPa)

t# max = +7.785E-01
INSTRUMENTED IMPACT TEST

I28(I2B)

\[ V = 0.62 \text{ Ft/s} \] (24.4 mm/s)
\[ Z = 0.010 \text{ Ft} \] (3.2 mm)
\[ \rho = \text{max} = 1.8636\text{E}+08 \]
\[ E = 8.616\text{E}+03 \text{ kN} \]
\[ b = 0.101 \text{ Ft} \] (40.8 mm)
\[ a = \text{max} = 2.3383\text{E}+01 \]
\[ L = 1.165 \text{ Ft} \] (355.1 mm)
\[ B = 7.856\text{E}+04 \text{ Lb/Ft} \] (3.753E+4 MPa)
\[ t = \text{max} = 7.6682\text{E}+01 \]
INSTRUMENTED IMPACT TEST

I2B(I2B)

VD= 0.02 Ft/s (2444.5 mm/s)
Z= 0.18 Ft ( 46.8 mm)
F max=+1.3689E+06

H= 0.41 Lbs (3.016E-3 Mgs)
b= .191 Ft ( 48.8 mm)
\( e1 \) max=+0.3003E-01

L=1.165 Ft (355.1 mm)
Q=765500E+4 Lbs/ft^2 (3.75yE+4 MPa)
t\# max=7.6682E-01
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