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Response of Laminated Composite Plates to Low-Speed Impact by Different Impactors

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An analytical procedure has been developed to determine the transient response of simply supported, rectangular laminated composite plates subjected to impact loads from airgun-propelled or dropped-weight impactors. A first-order shear deformation theory has been included in the analysis to represent properly any local short-wavelength transient bending response. The impact force has been modeled as a locally distributed load with a cosine-cosine distribution. A double Fourier series expansion and the Timoshenko small increment method have been used to determine the contact force, out-of-plane deflections, and in-plane strains and stresses at any plate location due to an impact force at any plate location. The results of experimental and analytical studies are compared for quasi-isotropic laminates. The results indicate the importance of including transverse shear deformation effects in the analysis for predicting the response of laminated plates subjected to both airgun-propelled and dropped-weight impactors. The results also indicate that plate boundary conditions influence the axial strains more significantly than the contact force for a dropped-weight impactor. The results of parametric studies identify a scaling approach based on impactor momentum that may account for the differences in the responses of plates impacted by airgun-propelled or dropped-weight impactors.

Introduction

THE effect of low-speed impact damage on the compression strength of laminated composite structures has been studied extensively by many researchers over the past several years. Test data show that the compression strength of composite structures can be reduced significantly by low-speed impact damage, even if the damage is not detectable by visual inspection. Current compression damage-tolerance design criteria for composite airframe structures are related to the impact energy or to the depth of the dent in the specimen caused by the impact event. Many of the researchers who have studied the effects of low-speed impact damage on composite structures used available equipment and materials of interest at the time of their studies. As a result, a wide range of specimen and impactor parameters has been studied, and the results of these studies have been reported in the extensive low-speed impact damage literature. For many of these investigations, specimen dimensions varied from study to study based primarily on the amount of material available. Specimen support conditions were also different. Some investigators simply dropped a weight of a given material and size onto their specimens from a given height to generate impact damage. Other investigators propelled a small impactor or projectile of a given diameter and material against their specimens at a given speed with a compressed-air apparatus or airgun to generate impact damage. The dropped-weight approach was intended to represent a dropped tool, and the airgun approach was intended to represent damage by hail stones or runway debris. Although the results of these studies all indicate that low-speed impact damage can degrade the compression strength of composite structures, there are enough differences in the results to indicate that a consistent analytical representation of the response of a composite structure to low-speed impact by a projectile or impactor is still needed. A consistent analytical representation of the response of a composite structure to low-speed impact and the resulting initiation of damage in that structure should account for different structural, impactor, and laminate parameters such as impactor mass, size, and speed; specimen or target geometry, materials, laminate stacking sequence, and boundary or support conditions; and the relative magnitudes of the impactor and target masses. Earlier analytical studies that were correlated with experimental results either focused on composite structures that were impacted by a relatively large mass at low impact speeds (e.g., Refs. 1–5) or on composite structures impacted by a relatively small mass at high impact speeds (e.g., Ref. 6).

In the present paper, an analytical procedure is developed for determining the impact response of laminated composite plates. The procedure is general enough to include all of the significant structural and impactor parameters. A first-order shear deformation theory has been used in this analysis to represent any local short-wavelength bending transient response phenomenon that may occur. The impact force has been idealized as a load that is locally distributed over a small area of the plate with a cosine-cosine distribution. The size of the loaded area is determined by an iterative procedure that accounts for the changes in the contact area between the impactor and the plate as the dynamic response of the plate develops. The contact force, out-of-plane deflections, and in-plane stresses and strains at any plate location due to an impact force at any plate location are determined using a Fourier series expansion and the Timoshenko small increment method. The analytical results are compared with experimental data for $[45/0/-45/90]_{6s}$ quasi-isotropic laminates made from a graphite-epoxy and a graphite-bismaleimide material system. Analytical and experimental results are presented and compared for both airgun and dropped-weight impact events. The effects of impact parameters such as impactor and target

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masses, impactor radius, and impactor speeds are discussed for both types of impact events. The influence and role of transverse shear deformation and boundary conditions on plate response for the two types of impact events are discussed.

Analysis Approach

The plate equations with first-order shear deformation effects given by Whitney and Pagano[7] are used as the basis for the analysis in the present paper. These first-order shear deformation effects are needed to account for the transverse shear deformations that can be very prominent in impact problems. It has been shown by Sun and Lai[8] that a plate theory that includes first-order shear deformation effects is adequate for representing transient wave propagation phenomena in an anisotropic plate subjected to impulsive loads. When rotatory inertia terms are neglected and simply supported boundary conditions are considered, a single nonlinear integral equation in terms of the contact force and the displacement function in position and time can be obtained. This equation can be solved numerically using the small increment method suggested by Timoshenko.[9] The details of the features included in this analysis method and the solution procedure are described in Ref. 10.

The impact load is assumed to have a cosine-cosine distribution as shown in Fig. 1 with the size of this locally distributed load determined using an iterative approach as the impact event progresses. A hertzian contact law was used to relate the contact force F, the static indentation depth α, and plate displacements w_1 and w_2 identified in Fig. 2. A convergence study was conducted for the present study using the plate dimensions of the test specimens and arbitrary impact and strain locations to account for variations in the test parameters. The influence of accurately modeling the locally distributed load and the number of terms to be used for the displacement functions in the x and y directions is presented in Ref. 10.

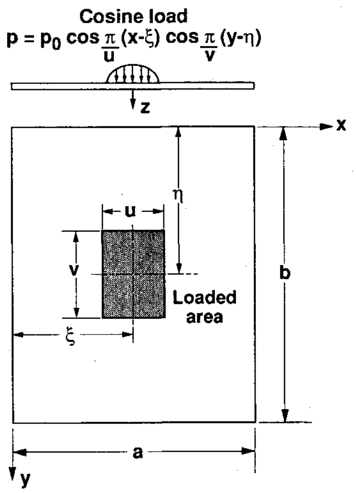


Fig. 1 Plate coordinates, and location and shape of loaded area.

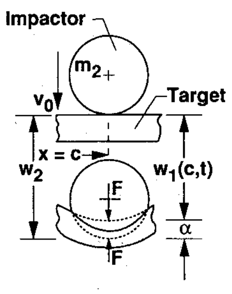


Fig. 2 Transverse impact of a spherical body with a curved contact surface.

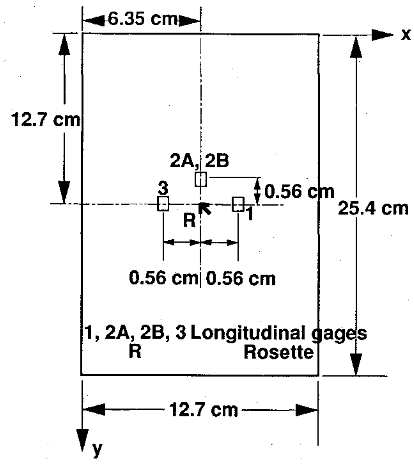


Fig. 3 Strain gage locations.

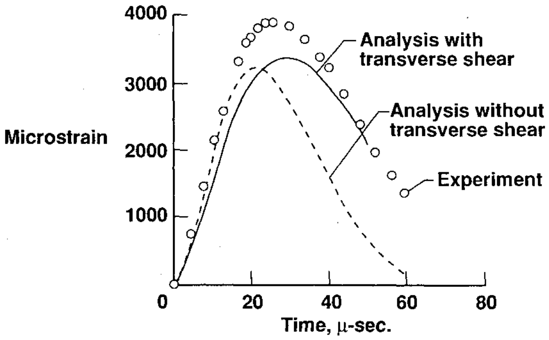
Experiments

Test Specimens

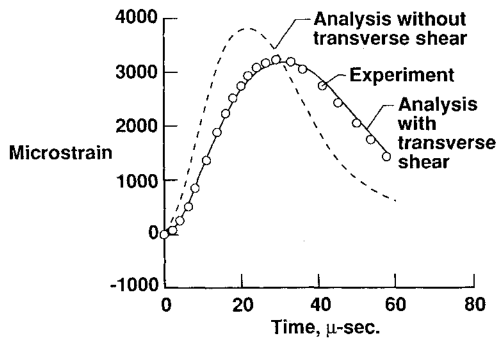
The specimens tested in this investigation were fabricated from commercially available unidirectional graphite fiber tapes preimpregnated with an epoxy or a bismaleimide resin. AS4/3502 graphite/epoxy and IM7/5260 graphite/bismaleimide material systems were used in this study. The mechanical properties for the AS4/3502 graphite/epoxy material system are as follows: longitudinal modulus, $E_1 = 138.0$ GPa; transverse modulus, $E_2 = 8.96$ GPa; in-plane shear modulus, $G_{12} = 5.99$ GPa; transverse shear modulus, $G_{23} = 3.51$ GPa; transverse shear modulus, $G_{13} = 5.99$ GPa; and major Poisson's ratio, $\nu_{12} = 0.3$. The mechanical properties for the IM7/5260 graphite/bismaleimide material system are as follows: longitudinal modulus, $E_1 = 153$ GPa; transverse modulus, $E_2 = 8.96$ GPa; in-plane shear modulus, $G_{12} = 5.10$ GPa; transverse shear modulus, $G_{23} = 3.30$ GPa; transverse shear modulus, $G_{13} = 5.10$ GPa; and major Poisson's ratio, $\nu_{12} = 0.3$. Unidirectional tapes were laid up to form $[45/0/-45/90]_{6s}$ quasi-isotropic laminated plates and cured in an autoclave using the resin manufacturers' recommended procedures. The resulting plates were ultrasonically inspected to establish specimen quality and then machined into 12.7-cm-wide by 25.4-cm-long rectangular specimens. Identification of commercial products in the present paper is used to describe the test specimens adequately. The identification of these commercial products does not constitute endorsement, expressed or implied, by NASA or the publisher of this article.

Apparatus and Tests

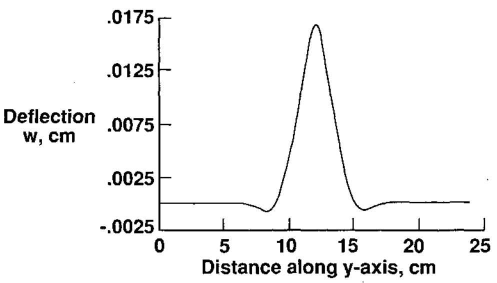
Knife-edge supports were used to provide simple-support boundary conditions for the test specimens. The knife-edge supports were attached to each edge of the specimens at locations 0.635 cm from each edge. Each specimen was impacted on one side of the specimen at the specimen center by either an airgun-propelled or a dropped-weight impactor. The airgun used in this study is based on the airgun described in Ref. 11. The airgun-propelled impactors were 1.27-cm-diam aluminum or steel balls that were propelled at the specimens at a given speed. The dropped-weight impactor consisted of a 1.18-kg dropped-weight assembly with an instrumented tup and 1.27- and 2.54-cm-diam steel impactor tips. For the dropped-weight impact tests, the dropped-weight assembly was raised to a desired height and released to impact the specimen. All specimens were instrumented with electrical resistance strain gauges mounted on the specimen surface opposite to the side to be impacted as shown in Fig. 3. Force and strain gauge data were recorded using a 4094 Nicolet digital oscilloscope.



a) Axial strain at plate center for 1.42 J impact energy with a 1.27-cm-diam steel ball



b) Axial strain at plate center for 2.17 J impact energy with a 1.27-cm-diam steel ball



c) Deflection profile along y-axis at x = 5.71 cm after 30 sec for 1.42 J impact energy with a 1.27-cm-diam steel ball

Fig. 4 Effects of transverse shear deformation on the response of 12.7-cm-wide by 25.4-cm-long graphite/epoxy plates subjected to airgun impact.

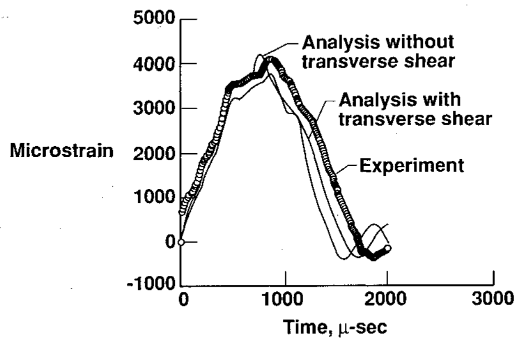
Results and Discussion

The analytical and experimental results of this study are presented and compared in this section. Analytical results are presented for 11.43-cm-wide by 24.13-cm-long plate models since the knife-edge supports for the test specimens are located 0.25 in. from the actual specimen boundaries. Thus, for a perfect central impact, the analytical coordinates for the impact site are $x = 5.71$ cm and $y = 12.06$ cm in Fig. 1. The analytical formulation presented in a previous section is for specially orthotropic plates where the coupling stiffnesses D_{16} and D_{26} are assumed to be zero. The D_{16} and D_{26} terms are not zero for quasi-isotropic specimens, but they are neglected in the analysis since they are small.

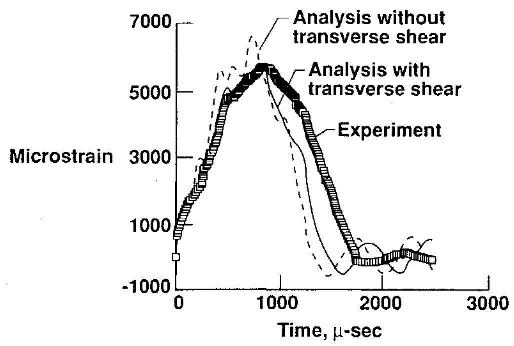
Transverse Shear Deformation Effects

The test specimens used for studying transverse shear deformation effects for both the airgun and dropped-weight impact cases are made from AS4/3502 graphite/epoxy material. The axial strains opposite to the point of impact by a 1.27-cm-diameter steel-ball airgun impact with 1.42 and 2.17 J of impact energy are shown in Figs. 4a and 4b as a function of time. For 1.42 J of impact energy, the initial parts of the analytical strain profiles with and without transverse shear deformation effects coincide with one another and also with the experimental data represented by the open symbols. The data beyond 10 μs indicate that the phase of the analytical strain profiles with and without transverse shear deformation effects is significantly different because of the natural frequency reduction associated with including transverse shear deformation effects in the analysis. Although the magnitudes of the differences in strain between the experimental and analysis results with transverse shear deformation effects indicate a large discrepancy, the phase difference is negligible. The strain magnitudes are very sensitive to the location of impact, and part of this difference in strain magnitude is attributable to the difficulty in measuring the exact impact location for the airgun experiments. The axial strain results (axial gauge 2 in Fig. 3) for an impact energy level of 2.17 J are shown in Fig. 4b where good correlation is obtained between the experimental and analytical results with transverse shear deformation effects included. The strain magnitude corresponding to the 2.17-J impact energy is smaller than the 1.42-J impact energy mainly because the impact location for the former case was off center to the plate. The out-of-plane deflection profile corresponding to the 1.42-J impact energy level is shown in Fig. 4c. This curve corresponds to the time at which the maximum axial strain occurs in the plate and indicates the local nature of the plate deflection for this impact case. Even for this relatively small impact energy level, the ratio of the deflection half-wavelength λ to the plate thickness h is equal to 11. The value for the ratio λ/h decreases for increasing impact energy levels, and the value of this ratio corresponding to 2.95 J of impact energy is equal to 8.1. Even for isotropic materials, the transverse shear deformation effects affect the results by approximately 5% for a λ/h ratio of 10 (Ref. 12). The results just presented are consistent with the observation that classical plate theory is generally in error for ratios less than 20, for specially orthotropic laminates, and indicate that it is important to include transverse shear deformation effects in the airgun impact analysis. Transverse shear deformation effects cannot be neglected for laminated plates as suggested in Ref. 6.

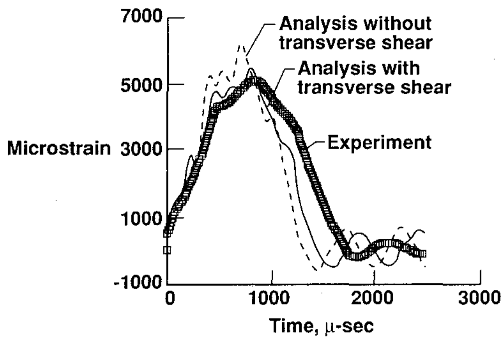
The dropped-weight impact results for 2.95 and 4.20 J of impact energy are presented in Figs. 5a–5c. The 2.95-J energy impact case is with a 1.27-cm-diam impactor, and the strain results measured by a strain gauge rosette (see Fig. 3) opposite to the point of impact are compared with the analytical results shown in Fig. 5a by the solid curves. These results indicate that the response due to the dropped-weight impactor occurs over a much longer time period than the response due to the airgun-propelled impactor and that transverse shear deformations do not have a significant effect on either the magnitude or the phase of the strain response for the dropped-weight impact with 2.95 J of impact energy. The phase is minimally affected since the impactor mass is large relative to the target mass. The axial strains for a dropped-weight impact energy level of 4.20 J with different impactor tip diameters are shown in Figs. 5b and 5c. The 2.54-cm-diam impactor tip results in increased contact area and, hence, a reduction in the measured surface strains opposite to the point of impact. Transverse shear deformations only influence the magnitude and not the phase of the response for cases with 1.27-cm- and 2.54-cm-diam impactor tips, suggesting that the transverse shear deformation effects are important as the energy level is increased. The λ/h ratios calculated from the out-of-plane deflection curves corresponding to the 2.95- and 4.20-J impact energy levels are 16 and 15, respectively. Although these ratios are larger than the λ/h ratios for the airgun impact cases with smaller energy levels, transverse shear deformation effects still appear to be important. Since including transverse shear deformation effects has provided better correlation between the analytical and experimental results for the quasi-isotropic laminates for both the airgun and dropped-weight impact tests, all subse-



a) Axial strain at plate center for 2.95 J impact energy with a 1.27-cm-diam steel ball



b) Axial strain at plate center for 4.20 J impact energy with a 1.27-cm-diam steel ball



c) Axial strain at plate center for 4.20 J impact energy with a 2.54-cm-diam steel ball

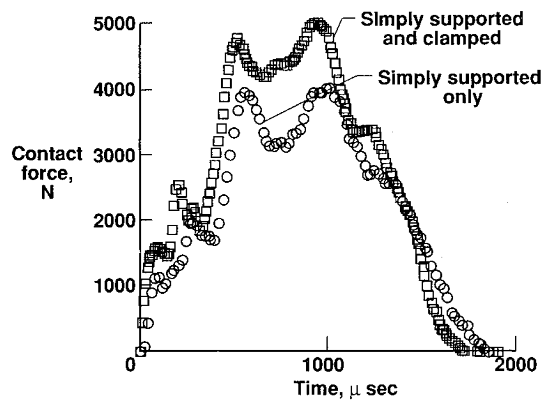
Fig. 5 Effects of transverse shear deformation on the response of 12.7-cm-wide by 25.4-cm-long graphite/epoxy plates subjected to dropped-weight impact at plate center.

quent analytical results include transverse shear deformation effects. The analysis procedure developed in the present paper is for specially orthotropic laminates, and the need for including transverse shear deformation effects for this class of laminates is well documented (e.g., Refs. 8 and 13).

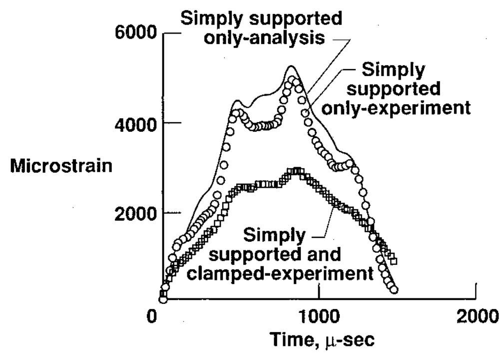
Effects of Boundary Conditions

The contact force and axial strain profiles opposite to the point of impact for an AS4/3502 graphite/epoxy plate impacted by a dropped weight with 2.95 J of impact energy are shown in Fig. 6 for two different boundary conditions. The boundary conditions considered include a case with all four sides simply supported and a case with the two long sides of the plate simply supported and the two short sides clamped. The experimental contact force results for the two boundary conditions are shown in Fig. 6a. The experimental and analytical results for the axial strain profiles for the two types of boundary conditions are shown in Fig. 6b. The analytical results are only for the plate with all sides simply supported. The contact forces are higher and the strains are lower for the clamped and simply supported plate compared with the simply supported plate. This is due to the interaction between membrane and bending stresses that results as a consequence of clamped boundary conditions. These results for contact forces are different by 24%, whereas the axial strains opposite to the point of impact are different by a factor of 2 for the two sets of boundary conditions. The analytical results for the plate with all sides simply supported compare well with the experimental results. These results indicate that the strains for a plate impacted by a dropped weight are significantly affected by the boundary conditions.

The experimental axial strain results for an IM7/5260 graphite/bismaleimide specimen supported with two different sets of boundary conditions and subjected to an airgun impact with 2.95 J of impact energy and the analytical results for simply supported boundary conditions are shown in Fig. 7. The impactor is a 1.27-cm-diameter steel ball for this example. These results indicate that the boundary conditions influence the response to a small extent, but it is suspected that part of the difference in strain results is a result of the actual impact location being slightly different from the intended central impact location. It appears that the transient out-of-plane deformation for the plate impacted by an airgun-propelled impactor is very local and that the contact force and axial strains are not significantly influenced by boundary conditions during the time period when most of the damage is inflicted on the plate.



a) Contact force profiles



b) Axial strain profiles

Fig. 6 Influence of boundary conditions on the response of 12.7-cm-wide by 25.4-cm-long graphite/epoxy plates subjected to 2.95 J impact energy by a 1.27-cm-diam steel dropped-weight impactor at plate center.

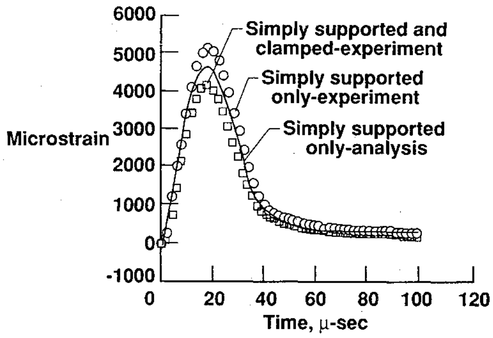
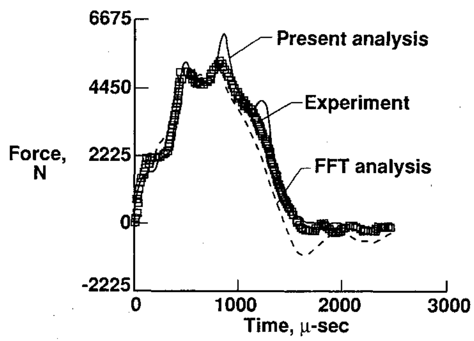


Fig. 7 Influence of boundary conditions on the axial strain of 12.7-cm-wide by 25.4-cm-long graphite/bismaleimide plates subjected to 2.95 J impact energy with a 1.27-cm-diam airgun-propelled steel ball.



a) Contact force for 1.27-cm-diam steel dropped-weight impactor at 2.95 J energy

b) Contact force for airgun impact with a 1.27-cm-diam steel ball at 3.20 J impact energy

Fig. 8 Comparison of contact force profiles for 12.7-cm-wide by 25.4-cm-long graphite/epoxy plates subjected to impact at plate center.

Contact Force

The contact force for the airgun impact tests could not be measured using conventional force transducers. However, the surface strains on the surface opposite to the point of impact can be measured accurately using strain gauges as illustrated in Figs. 4a, 4b, and 7. These strain gauge data can be used to reconstruct or recreate the contact force for the airgun impact tests using an inverse method that uses strain gauge data from the tests and a fast Fourier transform (FFT) approach developed by Doyle.[14] To verify this approach for recreating the airgun test contact force, the method has been used to recreate the contact force using strain profiles measured from a dropped-weight impact test. A measured contact force profile for a 0.66-cm-thick IM7/5260 graphite/bismaleimide test specimen that was impacted with 2.95 J of impact energy using a dropped weight is shown in Fig. 8a. The 1.18-kg dropped-weight device with a 1.27-cm-diameter steel tip was dropped from a 25.4-cm height to generate this impact energy level. The contact force profile predicted by the present analysis and the contact force profile reconstructed from the experimental strain data are also shown in the figure. The correlation between the measured contact force profile and the contact force profiles predicted by the FFT analysis and the present analysis is very good. This correlation illustrates that the contact force associated with a dropped-weight impactor can be estimated accurately from strain gauge data using the contact force reconstruction method.

A comparison of the contact force profiles predicted by the present analysis and the FFT analysis of strain gauge data for an airgun impact example is shown in Fig. 8b. For this example, an IM7/5260 graphite/bismaleimide plate has been centrally impacted by a 1.27-cm-diam steel ball with an impact speed of 46.5 m/s to generate an impact energy of 3.20 J. The comparison between the two contact force profiles is good.

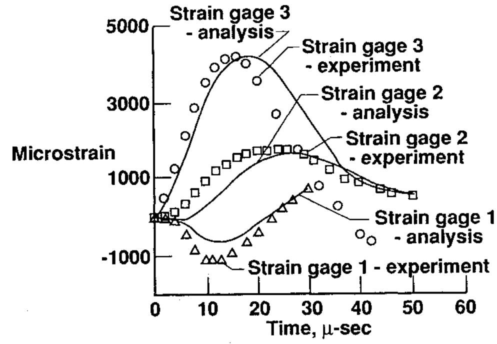


Fig. 9 Comparison of strain profiles for a 12.7-cm-wide by 25.4-cm-long graphite/epoxy plate at three locations for an off-center airgun impact with a 1.27-cm-diam aluminum ball at 37.82 m/sec speed.

In-Plane Strains

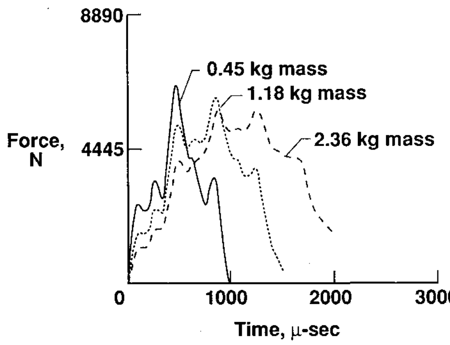
Controlling the trajectory of an airgun-propelled or a dropped-weight impactor well enough to strike a specimen precisely at the desired impact site has proven difficult to accomplish in the laboratory with currently available equipment. In practice, the impact site location is not necessarily at the center of the plate, and the strains and deflections of interest may be at any plate location. The present analysis is capable of predicting the deflections and strains at any plate location caused by an impact event at any impact site location. By providing the measured impact site and strain gauge locations, it is possible to calculate the plate transient response. An airgun impact example with an off-center impact site location is used to demonstrate this capability of the present analysis. A 0.6-cm-thick AS4/3502 graphite/epoxy plate is impacted by a 1.27-cm-diam aluminum ball with an impact speed of 37.82 m/s at $x = 4.95$ cm and $y = 12.06$ cm near strain gauge 3 (see Fig. 3). The corresponding experimental and analytical strain results are compared in Fig. 9. The maximum strain is tensile and is measured by strain gauge 3 near the impact site. The strain measured by strain gauge 1, which is farthest from the impact site, is first compressive and then tensile. The strain measured by strain gauge 2 has values of strain that are between the strains measured by strain gauges 1 and 3. Comparing the predicted and measured strain data shown in Fig. 9 indicates that the present analysis can predict the in-plane strains at any arbitrary point on the plate for off-center impact sites with reasonable accuracy.

Parametric Studies

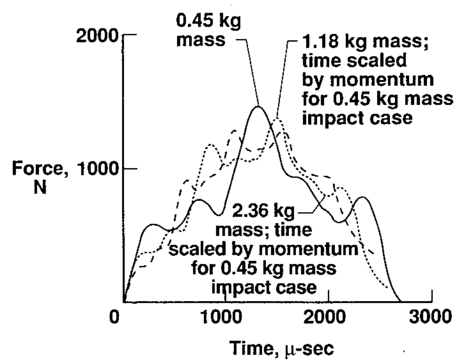
The agreement between the experimental and analytical results presented in the previous sections indicates that the present analysis represents the transient response of impacted composite plates well enough to use the analysis to conduct parametric studies. The results of these parametric studies are used to help understand better the differences in airgun-propelled and dropped-weight impact behavior and to understand the effects of changing other impact-related parameters on plate response. In these parametric studies, the contact forces and axial strains opposite to the point of impact are compared for different impactor geometries, materials, and speeds so that results can be compared on a consistent basis for different airgun-propelled and dropped-weight impact cases. All analytical results for these parametric studies are for a 12.7-cm-wide by 25.4-cm-long 48-ply-thick quasi-isotropic AS4/3502 graphite/epoxy plate subjected to a central impact force. Different impact energy levels for the airgun impact cases are obtained by varying the speeds for a given impactor mass. Impact energy levels for the dropped-weight impact cases are obtained by varying the heights from which the impactor is dropped.

The effect of different dropped-weight impactor masses on the response of the plate at a given 2.95-J impact energy level is shown in Figs. 10a and 10b. The impactor has a 1.27-cm-diam steel tip. Masses of 0.45, 1.18, and 2.36 kg were dropped from the appropriate heights required to generate the desired 2.95-J impact energy level. The terminal velocities of the dropped weights are 3.60, 2.23, and 1.57 m/s, respectively. These results indicate that the contact force and strain responses extend over longer time periods as the dropped-weight mass increases, which suggests that the impactor mass dominates the plate response of a low-speed dropped-weight impact event. The response time for which the maximum value of the contact force or strain response occurs also increases as a function of the impactor mass. However, the magnitudes of the maximum values of the contact force and strain response are within 5% of each other for all of the cases presented here. These results can be compared directly with one another by normalizing the time scale by the ratio of the appropriate impactor momenta as shown in Figs. 10c and 10d. Here, the responses corresponding to the 1.18- and 2.36-kg impactors are scaled by the ratios of their momenta to the momentum for the 0.45-kg mass impactor. These results show that the correspondence between the response results for these low-speed dropped-weight impact cases is excellent when scaled by the impactor momentum. The effect of increasing the dropped-weight impact energy level on the plate response for a given dropped-weight mass is shown in Fig. 11a. These results indicate that only the magnitude of the contact force and not its temporal distribution changes with impact energy, suggesting that a change in impactor speed dominates this response. The contact force results can be compared directly with one another by normalizing the contact force by the ratio of the appropriate impactor momenta, or impactor speeds since the impactor mass is constant in this case, as shown in Fig. 11b. Here, the responses corresponding to the 4.20- and 5.42-J impact energy cases are scaled by the appropriate impactor momentum ratios to establish a correspondence with the 2.95-J impact energy case. A similar comparison for strain results for the point opposite to the impact site is obtained when the results are scaled by the appropriate impactor momentum ratios. The excellent correlation of these momentum scaled results suggests that low-speed dropped-weight impact results can be compared on a consistent basis by scaling the appropriate response quantities or response time by the impactor momentum.

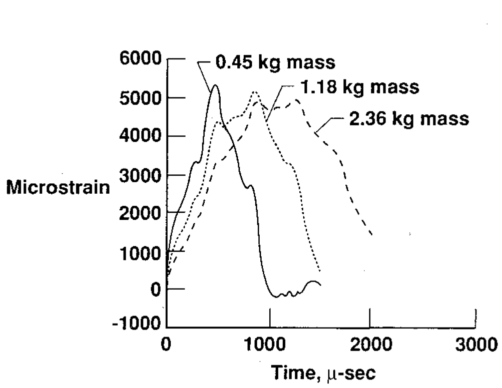
The axial strains opposite to the point of impact are compared in Fig. 12a for 1.27-cm- and 2.54-cm-diam airgun-propelled steel impactors with 2.95, 4.20, and 5.42 J of impact energy. These results indicate that the responses of airgun-propelled impactors are not comparable on an impact energy basis. A plate response due to a given impactor with a given impact energy level, such as 2.95 J, can be compared with the plate responses for other impact energy levels by scaling the response quantities by the appropriate corresponding impactor momentum ratio in the same manner as the dropped-



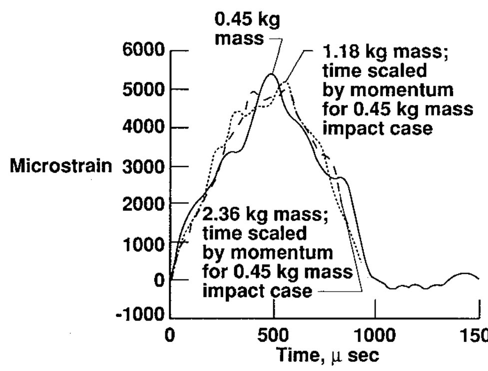
a) Contact force profiles



c) Comparison of contact force profiles with scaled time parameter for impacts using 0.45 kg, 1.18 kg and 2.36 kg masses

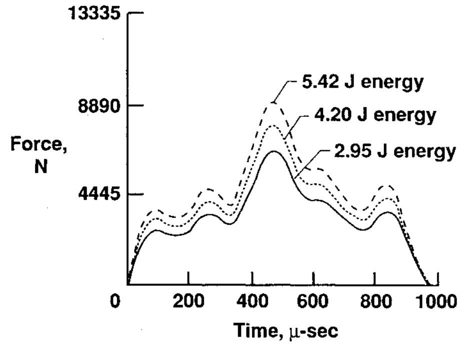


b) Axial strain profiles

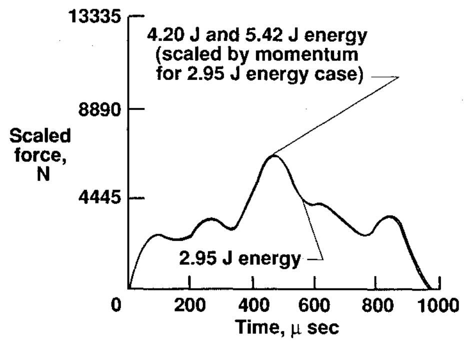


d) Comparison of axial strain profiles with scaled time parameter for impacts using 0.45 kg, 1.18 kg, and 2.36 kg masses

Fig. 10 Comparison of contact force and axial strain profiles for 12.7-cm-wide by 25.4-cm-long graphite/epoxy plates subjected to 2.95 J dropped-weight impact at plate center using 0.45 kg, 1.18 kg, and 2.36 kg masses.

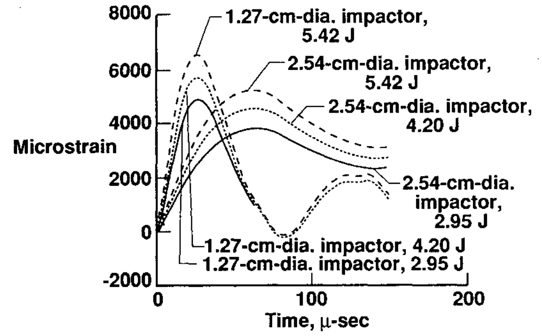


a) **Contact force profiles**

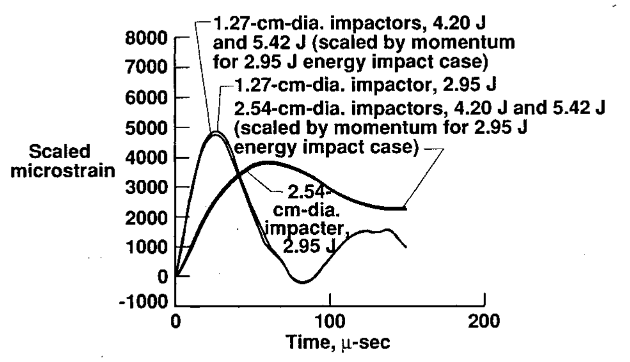


b) **Contact force profiles with scaled force parameter for 4.20 and 5.42 J impact energies**

Fig. 11. Comparison of contact force profiles for 12.7-cm-wide by 25.4-cm-long graphite/epoxy plates subjected to increasing dropped-weight impact energy levels using a0.45 kg mass impactor.



a) **Axial strain profiles**



b) **Axial strain profiles with scaled strain parameter for 4.20 and 5.42 J impact energy levels**

Fig. 12 Comparison of axial strain profiles for 12.7-cm-wide by 25.4-cm-long graphite/epoxy plates subjected to airgun impacts at 2.95, 4.20, and 5.42 J impact energy levels using 1.27-cm- and 2.54-cm-diam steel ball impactors.

weight impactor results. The momentum scaled strain responses for this example are shown in Fig. 12b, and the results for each airgun-propelled impactor correlate very well. The momentum scaled results for both the dropped-weight and the airgun-propelled impactors indicate that the transient plate responses can be related to one another based on impactor momentum and not on impact energy level.

Concluding Remarks

An experimentally validated analysis method has been developed to determine the transient response of simply supported, rectangular laminated composite plates subjected to low-speed impact. A first-order shear deformation theory has been used for the plate analysis, and the impact load is modeled as a locally distributed force with a cosine-cosine distribution. The analysis method developed can predict responses at arbitrary plate locations corresponding to impact at an arbitrary point. The transient response of plates subjected to impact loads from both airgun-propelled and dropped-weight impactors has been investigated for different impactor parameters and plate boundary conditions.

Comparing analytical and experimental results in the study indicates that the local or short-wavelength transient response of a plate impacted with an airgun-propelled impactor requires that transverse shear deformations be accounted for in the analysis. Both the magnitudes and time histories of the impactor contact force and strains on the plate surface opposite to the impact site are affected by transverse shear deformations with relatively high impact energies, and the magnitudes of these response quantities are affected even for lower impact energies. This phenomenon occurs because the transient wavelengths of the local out-of-plane deflection decrease with increasing impact energy levels. For plates impacted by dropped-weight impactors, only magnitudes of the response quantities were affected by not including transverse shear deformation effects in the analysis. The analytical results with transverse shear deformation effects included in the analysis agree well with the experimental results, confirming that it is important to include these higher-order effects in the analysis to represent the physics of the impact event properly.

The effects of boundary conditions on the plate transient response are more significant for plates impacted by a dropped-weight impactor than by an airgun-propelled impactor. The strains on the plate surface opposite to the impact site for plates with two edges simply supported and two edges clamped are only half the values of the corresponding surface strains for a plate with all simply supported edges, if the plate is impacted by a dropped-weight impactor. The response of a plate impacted by an airgun-propelled impactor is very local, and different boundary conditions have a minimal influence on the strains opposite to the impact site. The effect of boundary conditions on plate response indicates the importance of imposing the appropriate plate boundary conditions for tests when studying impact response behavior with a dropped-weight impactor.

The results of a parametric study indicate that the transient response of a plate is affected by varying impactor parameters. The response of plates impacted at the same impact energy level by dropped-weight impactors of different masses is dominated by the impactor mass rather than the impactor speed. For these mass-dominated events, the response corresponding to a larger mass impactor is sustained over a longer period of time than the response corresponding to a smaller mass impactor that has the same impact energy. The maximum values of the response quantities occur at a later time for the larger mass impactors. When a plate is impacted at different impact energy levels using a dropped-weight impactor of a given mass, the parameter that most influences the plate response is the impactor speed. For these impactor-speed-dominated events, the magnitude of the plate response increases with increasing impactor speed without affecting the time at which the maximum response occurs. The same types of mass- and speed-dominated responses also occur for plates impacted by airgun-propelled impactors. It was found that both the mass- and speed-dominated transient responses of plates impacted by airgun-propelled and dropped-weight impactors can be correlated by scaling the appropriate response parameters by the impactor momentum. For an impactor-mass-dominated impact event, the response time is scaled by the impactor momentum, but for an impactor-speed-dominated impact event, the impactor contact force or surface strain is scaled by the impactor momentum.

The results of this study indicate that the observed differences in the behavior of composite plates impacted by airgun-propelled and dropped-weight impactors can be explained by sound structural mechanics principles.

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