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Ballistic Impact of Thin-Walled Composite Structures

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Methods of analysis have been developed that provide the means to determine whether a ballistic impactor of known shape, mass, and striking velocity will penetrate a given thin-walled composite material structure and if it does, what the residual velocity of the impactor will be. The methods developed require performing penetration experiments at two striking velocities (with suitable replicates for statistical purposes) for any given composite structural target. From this minimum number of tests, one can predict the penetration, nonpenetration, and residual velocity of an impact at other striking velocities. This provides a dramatic reduction in the amount of expensive testing required to study penetration due to ballistic impact. It also provides a less expensive and less time-consuming means to select the best material system and structural configuration to resist ballistic impact. Finally, it shows that the physics of ballistic impact and the penetration phenomena is modeled satisfactorily. These methods also accurately predict the ballistic limit.

Introduction

CONSIDERABLE attention has been given to ballistic impact into a variety of materials and structures. Three good sources of study for that research are Refs. 1–3. In 1975, Vinson and Zukas[4] studied ballistic impact of blunt impactors into textile body armor. In their research they developed methods by which to analyze the ballistic impact effects into woven Kevlar® and nylon targets and applied the methods to the experimental data of Maheux et al.,[5] the Mellon Institute,[6] and Roylance et al.[7] In their analysis methods, Vinson and Zukas[4] determined that in the flexible textile protection systems the ballistic impactor formed a conical shell, wherein the nose end of the conical shell geometry is determined by the impacting projectile, whereas the aft end of the conical shell geometry is determined by the shear wave propagation in the textile with time. The membrane forces generated in the shell decelerate the projectile until either the maximum tensile strain of the textile fibers is reached (penetration) or the velocity of the ballistic impactor reaches zero (projectile capture). In any case, the mechanics is described satisfactorily by using microsecond time increments, and such descriptors as maximum displacement, affected area, and equivalent shell strain as a function of time are outputs of the analysis methods.

When the calculated projectile velocity diminishes to the experimentally measured residual velocity, the corresponding value of the calculated maximum macroscopic shell strain is the shell strain at penetration. The most interesting result is that this maximum shell strain at penetration varies linearly with striking velocity for all cases studied to date. This linearity of maximum strain with respect to the striking velocity is an observed consequence of the analysis, not an assumption a priori. The failure strain is a function of impact velocity because the higher the impact velocity, the higher the spectrum of strain rates to which the material is subjected. Increases in strength and stiffness with strain rate are well known. Only if the material were strain rate insensitive would the failure strain not be a function of the impact velocity. However, in that case, the method could still be used. By plotting the maximum strain as a function of the striking velocity of the projectile, it was found that the maximum strain is linear over the entire range of striking velocities. This was true for 1- and 12-ply nylon cloth targets, as well as 1-, 2-, 4-, 6-, 12-, and 24-ply Kevlar cloth targets.

Thus by merely performing penetration experiments at two different striking velocities (with suitable replicates for statistical purposes), one has sufficient information from the linear strain to failure as a function of striking velocity plot to predict the behavior of any other impactor striking the same target. This was studied in detail by Taylor[8] and Taylor and Vinson.[9]

More recently, Cantwell and Morton,[10] Zhu et al.,[11] Joshi and Sun,[12] and Lee and Sun[13–15] have studied the ballistic impact into various composite material structures.

It is easily seen that in a polymeric-matrix-fiber-reinforced composite, the strain energy developed in the matrix is very small (a very few percent) compared with the strain energy developed in the fibers, either in bending or in membrane tension. Furthermore, the membrane strain energy is sufficiently large that bending strain energy in the target can be ignored. Therefore the model originally developed for a flexible textile fabric also applies to the fiber-reinforced continuous fiber composite: the matrix simply does not increase the protection against ballistic impact. All of the ballistic resistance is in the tensile membrane strain energy of the fibers. Therefore the methods developed in Ref. 4 apply to fibrous polymer matrix composite structural targets as well. When Lee and Sun[16] published the experimental data of their recent study of dynamic penetration of graphite/epoxy laminates impacted by a blunt ended projectile, the methods of analysis developed in Ref. 4 could be evaluated.

Mechanics of the Ballistic Impact

Upon the impact of the ballistic projectile into the composite material structure, as shown in Fig. 1, a conical shell forms and proceeds to develop until either the projectile penetrates the target or its velocity is reduced to zero. This conical shell is primarily in a state of membrane stress and strain, and the resistance to penetration is almost exclusively due to membrane strain energy. At the front of the conical shell the radius R_1 is determined by the configuration of the projectile and is defined as the radius at the junction between impactor and target. If the projectile's nose is curved, then R_1 will change with time, depending on the cone half angle β. The same locus is also labeled the meridional slant distance y_1, measured from the apex.

The base radius of the conical shell is determined to be the distance the shear stress wave has propagated in the composite material target from the point of initial impact ($t = 0$) at time t. It can be given as $R_2 = R_1(t = 0) + C_s t$, where C_s is the shear wave velocity. This can usually be taken as $C_s = \sqrt{(G_{yz}/\rho_m)}$, where G_{yz} is the transverse shear modulus in the meridional direction and ρ_m is the mass density of the composite material. When possible, G_{iz} should be the dynamic transverse shear modulus at the strain rate occurring at that time; if not available, of course the static value must be used for any calculations. The slant height y_2 measured from the apex corresponds to the locus of points termed R_2.

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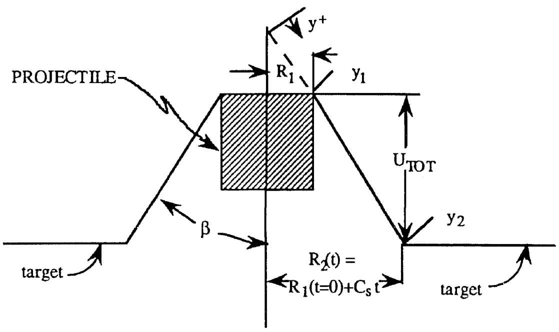

Fig. 1 Ballistically impacted target deformation pattern.

The impact phenomenon occurs in such a time frame that the natural frequencies and vibration modes of the shell are not excited appreciably; hence a quasistatic analysis can be used. Also, since the entire event takes place during a time that the shear wave has progressed only 2 in. or 0.05 m or less from the point of impact, the overall structural dimensions and boundary conditions are not relevant.

In the conical shell of Fig. 1 loaded vertically at $r = R_1$ by an axial load per unit circumference $V(y_1)$ only, it would be opposed by another vertical load per unit circumference $V(y_2) = (y_1/y_2)V(y_1)$. However, in the dynamic problem here, the vertical load $V(y_1)$ occurs because the projectile is stretching the composite conical shell a distance U_{TOT} from its undisturbed horizontal plane. Thus in this dynamic case instead of a $V(y_2)$, there exist inertial forces of the target mass being moved vertically out to the radius R_2. However, only the strains in the target material in the vicinity of the impactor are described here because that is where they are maximum. Furthermore, bending stresses caused by the impactor are not included in the following because of the dominating nature of the membrane action.

Knowing the striking velocity (V_s) of the projectile at $t = 0$, at some small time t later, the projectile will have caused some vertical deflection in Fig. 1 of U_{TOT}. From membrane conical shell theory (see Refs. 4, 17, and 18), the maximum strain in the conical shell formed by the target is the meridional membrane strain ε_y^0 at the projectile target interface given by

$$\varepsilon_y^0(y_1) = \frac{R_1 V(y_1)}{Eh \sin\beta \cos\beta}\frac{1}{y_1} = \frac{U_{\mathrm{TOT}}\cos\beta}{y_1 \ln(y_2/y_1)} \tag{1}$$

where E is the modulus of elasticity in an isotropic material and, in the case of a composite material, is the in-plane modulus in the shell meridional direction, and h is the target thickness. It is clear that as the projectile deflects the composite material target, both the level of strain and the strain rate change appreciably with time.

Defining the total axial displacement of the conical shell to be $U_{\mathrm{TOT}} = U(y_2) - U(y_1)$, then from shell theory,

$$U_{\mathrm{TOT}} = \frac{R_1 V(y_1)}{Eh \sin\beta(\cos\beta)^2}\ln\left(\frac{y_2}{y_1}\right) \tag{2}$$

Finally, it is seen that the axial load per unit circumference caused by the projectile that generates the conical shell deformation pattern also decelerates the projectile as stated earlier. The projectile deceleration at any time t then can be written as

$$a_p = -\frac{2\pi R_1 V(y_1)}{m_p} \tag{3}$$

where m_p is the mass of the projectile.

From the mechanics outlined, a computational procedure can now be formulated.

Computation Procedure

Consider a projectile impacting a composite material structure. The following quantities are needed: 1) mass of the projectile, 2) shape of the projectile, 3) striking velocity of the projectile, 4) in-plane elastic tensile modulus of the composite target, 5) transverse shear modulus of the composite target, 6) density of the target composite, and 7) thickness of the composite target.

The procedure to analyze the ballistic impact phenomenon is as follows.

1) Select a time interval $\breve{}t$ to use. Experience suggests a time step of 1 μs.

2) Calculate $U_{\mathrm{TOT}}(t) = v_p(t)\breve{}t$, where $v_p(t)$ is the projectile velocity at time t.

3) Calculate $R_2(t) = R_1(t) + C_s\breve{}t$, where $C_s = \surd(G_{yz}/\rho_m)$.

4) Calculate

$$\beta(t) = \tan^{-1}\left(\frac{R_2(t) - R_1(t)}{U_{\mathrm{TOT}}(t)}\right)$$

5) Calculate

$$\varepsilon_y^0(y_1, t) = \frac{U_{\mathrm{TOT}}(t)\cos\beta(t)}{y_1(t)\ln(y_2/y_1)} = \frac{U_{\mathrm{TOT}}(t)\sin\beta(t)\cos\beta(t)}{R_1(t)\ln(y_2/y_1)}$$

remembering that $y_2/y_1 = R_2/R_1$.

6) Calculate

$$V(y_1, t) = \frac{Eh}{R_1(t)}\frac{U_{\mathrm{TOT}}(t)\sin\beta(t)[\cos\beta(t)]^2}{\ln(y_2/y_1)}$$

7) Calculate

$$a_p(t+1) = -\frac{2\pi R_1(t)V(y_1, t)}{m_p}$$

8) For the next time, $t + 1 = t + \breve{}t$, calculate $v_p(t+1)$, where $v_p(t+1) = v_p(t) + a_p(t)\breve{}t$.

9) For $t + 1$, calculate

$$U_{\mathrm{TOT}}(t+1) = U_{\mathrm{TOT}}(t) + v_p(t)\Delta t + \tfrac{1}{2}a_p(t)(\Delta t)^2$$

10) Calculate $R_2(t+1) = R_2(t) + C_s\breve{}t$.

11) Repeat steps 4–10 until either the projectile velocity is zero or the ultimate strain of the composite is exceeded, which is the strain corresponding to an experimentally determined residual velocity.

Experimental Verification

As stated previously, essentially the same mechanics was employed to develop an understanding of the ballistic impact into woven fabric structures. Since the strain energy of projectile-deformed polymer matrix is insignificant compared with that of the deformed fibers in a composite, the same procedures should depict ballistic impact into polymer matrix composites. Experimental data of Lee and Sun[16] were used to test the hypothesis described previously. Lee and Sun utilized targets of Hercules AS4/3501-6 graphite epoxy, with a stacking sequence of $[0/90/45/-45]_s$. Their projectile was blunt ended and made from hardened 4340 steel. The projectile was 24 mm long and had a radius of 14.5 mm.

The in-plane tensile modulus of elasticity of the target is $E = 53.7$ GPa $= 7.78 \times 10^6$ psi; the transverse shear modulus of the target is $G_{iz} = 4.00$ GPa $= 0.58 \times 10^6$ psi; and the mass density of the target material is given by Lee and Sun[16] as 1.55 g/cm^3 $= 1.448 \times 10^{-4}$ lb s^2/in.^{4}. For the projectile, the radius is 0.285 in. (0.7249 cm) and its mass is 1.7358×10^{-4} lb s^2/in. (30.45 g).

Lee and Sun[16] performed experiments wherein types I and II were identical, i.e., 16 plies thick, and type III utilized 32 plies of the same material.

A typical computational sheet is shown in Ref. 19 for one of the Lee–Sun calculations, where a time step of 1 μs is sufficiently small to produce accurate results. Test no. 22 of the type I specimens was selected. The projectile striking velocity v_s was 79 m/s = 3110.24 in./s. As the projectile velocity reduces with time, it is seen that penetration occurred such that the residual velocity was $V_R = 65$ m/s = 2559.06 in./s. Therefore from the computational sheet it is seen that when the projectile velocity is V_R, the maximum strain in the target is 0.0058. Hence that is the failure strain by definition. Also of interest is that at that time, $U_{\mathrm{TOT}} = 0.1626$ cm only, $\beta = 87.4_i$, and R_2 is only 4.42 cm. The time to penetrate the target is only 2.3×10^{-5} s after impact. The impact and penetration of the composite target is a very localized phenomenon.

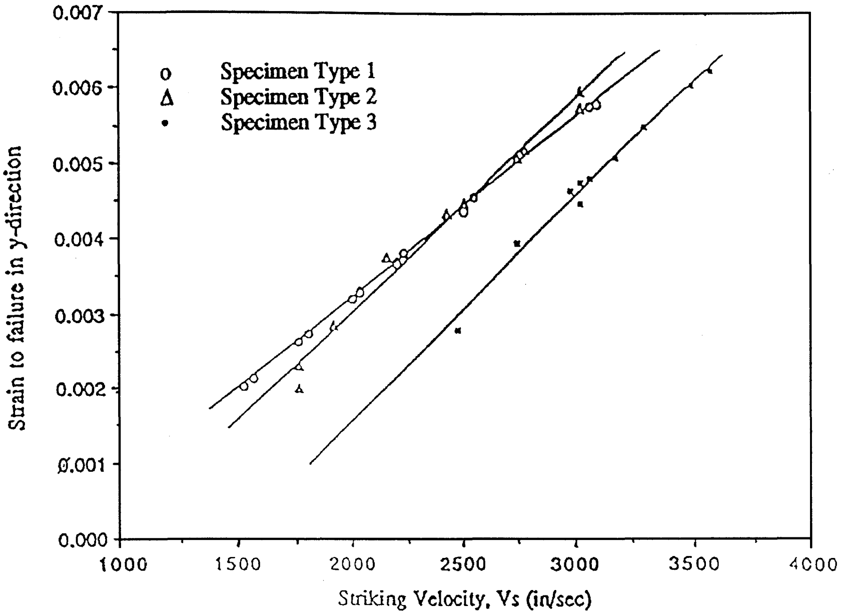

Fig. 2 Strain to failure as a function of striking velocity. Material: Hercules AS4/3501-6 graphite/epoxy with $[0/90/45/-45]_s$ with thickness of 2 mm (I, II) and 4 mm (III).

However, a most interesting result is shown in Fig. 2, where it is seen that for all of the Lee–Sun-type experiments wherein penetration occurred, the strain to penetration failure is a linear function of the striking velocity only. Each point shown is one of the experiments shown in Tables 3–5 of Ref. 19. The important fact is that for each line, any two of the Lee–Sun experiments would have established the line; then all of the other experiments prove that the methods work! For these experiments the equations for the penetration maximum strain ε^0_{yf} of these materials are determined to be as follows.

Specimen type:

I

$$\varepsilon^0_{yf} = -1.6073 \times 10^{-3} + 9.4334 \times 10^{-5} V_s, \quad R^2 = 0.999$$

II

$$\varepsilon^0_{yf} = -2.7087 \times 10^{-3} + 1.1191 \times 10^{-4} V_s, \quad R^2 = 0.985 \tag{4}$$

III

$$\varepsilon^0_{yf} = -4.5333 \times 10^{-3} + 1.1910 \times 10^{-4} V_s, \quad R^2 = 0.989$$

where V_s is in m/s. It is seen from the R^2 values that these equations are highly reliable.

Obviously one should use caution in extrapolating any relationships beyond the limits of striking velocity for which experiments have been performed. However, calculations show that if V_s increases, the strain to failure increases, such that $V_R \to V_s$. Reducing the striking velocity merely shows that at the ballistic limit and below, the strain to failure never is reached as the projectile velocity goes to zero, as discussed next.

Importance of Computational Method

Because of the linear relationship established for the failure strain as a function of the striking velocity, only penetration experiments at two different striking velocities are necessary to establish this line for a given composite material target structure. Then, using the computational methods developed, one may investigate what will occur if that same structure is impacted by any projectile of any mass, shape, or velocity. If in following the procedures outlined earlier the maximum strain reaches the failure value for that striking velocity as shown in Fig. 2 or calculated using Eq. (4) for these material–structural systems, then penetration will occur and the projectile velocity at the time of reaching that failure strain is the residual velocity. If that failure strain is never reached by the time the projectile velocity reaches zero, then penetration does not occur. It is as simple as that.

Now, numerous material–structural systems can be investigated with minimal effort (tests at two different striking velocities that penetrate the target times the number of replicates desired), and the best material system, stacking sequences, thicknesses, etc. can be determined with minimum cost and time.

It is seen that these simple procedures are far easier to use than finite element programs developed previously. Therefore considerable time and effort are saved in accurately determining whether penetration occurs and if it does, what the residual velocity is. At the very least, these methods provide an alternate solution to previous methods.

Determination of the Ballistic Limit

The ballistic limit can be defined as the striking velocity of a given projectile impacting a given target, resulting in a residual velocity of the projectile of zero. From experimental data, this velocity is sometimes called V_{50} (i.e., that velocity at which 50% of identical projectiles will penetrate a given target and 50% of the projectiles will not penetrate the target) and sometimes it is called V_L.

Using the computational methods described earlier, from Eq. (4) one can calculate the strain to failure (penetration) associated with any striking velocity of the Lee–Sun projectile striking each of the three targets. One then assumes various striking velocities and, following Table 6 of Ref. 19, calculates the strains with time until the unique striking velocity is found that results in a strain equal to the corresponding failure strain from Eq. (4) at a projectile velocity of zero. That is the ballistic limit for that projectile–target combination.

As an illustration, consider the type III experiments of Lee–Sun.[16] Using their procedures, the experiments predict a ballistic limit of 67 m/s. This was determined by averaging the predicted ballistic limit from each of the Lee–Sun tests on type III specimens listed again in Table 5 of Ref. 19. From this table it is seen that for a striking velocity of 67 m/s, the residual velocity experimentally should be approximately 23 m/s.

By the methods described herein, a ballistic limit of 54.3 m/s is predicted for the type III tests. Looking at Table 5 of Ref. 19, test 2 for $V_s = 55.0$ m/s, $V_R = 0$. Therefore the methods presented herein appear to predict V_L quite closely.

Conclusions

Methods of analysis to determine the ballistic resistance of thin-walled composite material structures have been developed and tested utilizing the results of independent experiments. It is seen that penetration experiments at only two different striking velocities (and replicates desired) are needed to establish the linear relationship for a target material's strain to failure as a function of striking velocity. Once a curve such as that of Fig. 2 is established for a material, the method can be used to investigate the effects of any other ballistic impact, providing the residual velocity, time to penetrate, radius of affected area, deflection at penetration, etc. The methods therefore provide a rational, relatively inexpensive means by which to select the best materials–structure combinations to thwart ballistic penetration. The same methods can be used for the study of sandwich configurations.

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