Recent Advances in High-Velocity Impact Perforation of Fiber Composite Laminates*

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In this paper, recent works on impact perforation of fiber composite laminates struck by foreign objects traveling at high speed have been reviewd. The review focuses on two major subjects in impact perforation research, i.e., an assessment of perforation characteristics and an understanding of the perforation process and its mechanisms. The target materials include glass, carbon, and aramid fiber-reinforced plastic composites, while the foreign objects consist of steel ball projectiles and cylindrical projectiles with a conical, hemispherical or flat tip. The ballistic limit velocity, residual velocity, and perforation energy obtained from the impact tests and predicted from the analytical and computer models are reviewed first. Then the perforation process and mechanisms are discussed based on the experimental observations and computer simulations. The present article provides state-of-the-art information in the rapidly developing field of impact perforation of fiber composite laminates, by referring mainly to literature published over the past decade.

Key Words : Fiber Composite Laminates, Impact Perforation, Foreign Object, Perforation Characteristics, Perforation Process and Mechanisms

1. Introduction

As fiber-reinforced plastic composites such as glass, carbon, and aramid fiber-reinforced plastics become increasingly popular for use in structural applications, they are also being considered for use in applications where the resistance against impact load is critical. In general, there are two forms of impact which may be potentially disastrous for structures: low velocity and high velocity. Low-velocity impact induces delamination damage inside the laminates, which, although barely visible from outside, leads to significant reductions in the compressive strength. This is known as the CAI (Compression After Impact) problem and has been extensively investigated by many researchers over the past two decades. Comprehensive reviews of low-velocity impact on composite laminates were presented by Abrate(1) and Cantwell and Morton(2), two works which address the literature reported up to the early '90s. High-velocity impact, on the other hand, form perforations in the structures, which may be fatal to the structural integrity of vehicles such as aircraft and ships, and for their occupants. There are relatively few studies on high-velocity impact of fiber composite laminates compared to those of low-velocity impact due to the complexity of the experimental setup and procedure.

The article is intended to provide a review of the recent works on impact perforation of composite laminates struck by foreign objects traveling at high speed. Particular emphasis is placed on understanding the perforation process and its mechanisms as well as on assessment of perforation characteristics.

2. Reviews of Research into Impact Perforation

Historically, ivestigations of impact perforation, often called ballistic impact, have been performed exclusively on metallic plates such as those of steel and aluminium. A comprehensive survey for

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penetration and perforation mechanics can be found in the paper by Backman and Goldsmith(3). Books by Zukas et al.(4),(5) deal with many fields of impact dynamics including penetration and perforation. Concrete and steel-reinforced concrete are also target materials for the study of penetration and perforation because these materials are of particular interest to the nuclear industry. Therefore, considerable effort was devoted to investigations of ballistic impact of these materials subjected to foreign objects such as missiles. A review of the penetration and perforation mechanics of these concrete target plates was performed by Kennedy(6). Studies on impact perforation and penetration conducted after the survey of Backman and Goldsmith were reviewed by Corbett, Reid and Johnson(7), and deal with metals, soils, concrete, and reinforced concrete. A broad overview of both analytical and numerical modeling for ballistic impact perforation was also given by Anderson and Bodner(8). Most of these review papers are concerned mainly with conventional structural materials such as metals and ceramics. In recent years, with the increasing use of fiber composite materials due to their superiority over conventional materials in terms of weight and strength, attention is also being paid to the penetration and perforation of fiber composite laminates. The ballistic impact of composite laminates was briefly reviewed by Abrate in his paper(9) on recent advances in the studies of impact on laminated composites.

3. Assessment of Perforation Characteristics

Since perforation characteristics are of critical importance in the design of protective structures such as nuclear reactor containment vessels, armor systems, and turbine rotor casings which are threatened by missiles such as projectiles and fragmentations, their assessment has been the major subject in the research on impact perforation. The perforation characteristics include ballistic limit velocity, residual velocity, perforation energy, specific limit energy, and failure mode. In the assessment of perforation characteristics, not only the experimental determinations but also the analytical and numerical predictions are important. Thus, many predictive models have been developed based on various approaches, which are classified into empirical formulation, analytical modeling, and computer simulation. Meanwhile, the perforation characteristics vary depending on the geometrical configurations and material properties of the projectile and target plate as well as the impact conditions such as impact velocity and incidence angle of the projectile. In addition, for fiber composite laminates, the kind of fiber and matrix, type of reinforcements, fabrication method and stacking sequence are also important factors affecting perforation characteristics. Therefore, in the following, the major perforation characteristics are described, focusing on the effect of these parameters. Various phenomenological models for predicting/estimating the perforation characteristics are also introduced.

3.1 Ballistic limit velocity

The ballistic limit velocity or ballistic limit is defined as the velocity beyond which a specified projectile perforates a specified target plate and below which it will not. Ballistic limit prediction is especially important and has been the focus of considerable effort in the study of impact perforation. Zhu et al.(10) performed experimental investigation of the dynamic penetration and perforation response of woven Kevlar/polyester laminated plates perforated by cylindro-conical projectiles. Figure 1 shows the results where the ballistic limit varies linearly with laminate thickness and is higher for a smaller striker due to its lower mass. On the basis of areal density, Kevlar has an equivalent ballistic limit velocity of 110 m/s, 20% greater than that for 3.175 mm-thick 2024-0 aluminium, since the ballistic limit of the aluminium plate struck by the 12.7 mm-diameter cylindro-conical projectile was reportedly about 90 m/s. A phenomenological model of the impact perforation was also developed by Zhu et al.(11). The computed results for the ballistic limit velocities for the Kevlar/

Table 1 Theoretical prediction of ballistic limits for Kevlar/polyester laminates

Thickness of laminates (mm)	Number of plies	Experimental results (m s^{-1})	Theoretical prediction (m s^{-1})
3.125	5	75	84
6.35	10	109	116
9.525	15	143.2	145
12.7	20	170	170

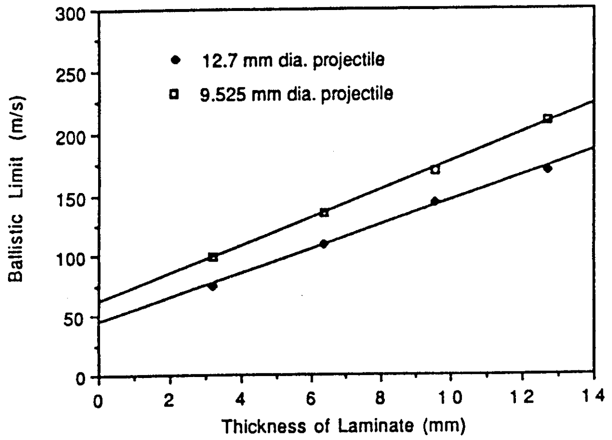

Fig. 1 Ballistic limits of Kevlar/polyester composites penetrated by 60° cylindro-conical projectiles with two different diameters

Table 2 Configuration of composite laminates

Specimen type	I	II	III
Layup	$([0/90/45/-45]_s)_2$	$([0/90/45/-45]_s)_2$	$([0/90/45/-45]_s)_4$
$\frac{\text{Span of specimen}}{\text{Diameter of projectile}}$	3	6	3
Thickness	2 mm (16 plies)	2 mm (16 plies)	4 mm (32 plies)

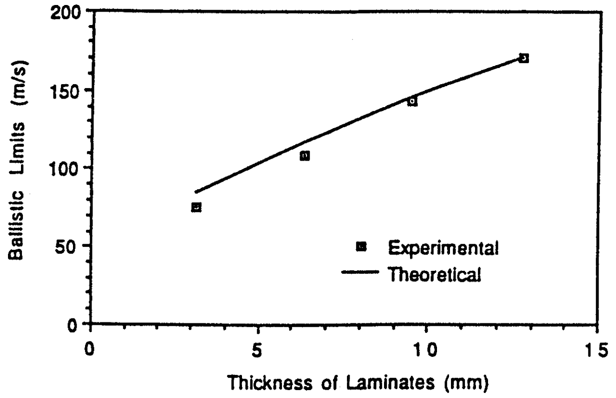

Fig. 2 Comparison of the ballistic limits of Kevlar/polyester laminates perforated by a 12.7-mm-diameter 60° cylindro-conical projectile

Table 3 Comparison of ballistic limit between experimental data and computational modeling for all three types of specimen

Ballistic limit (m/s)	Type I	Type II	Type III
Experiment (1)	42	47	67
Modeling (2)	41	50	60
$[(2)-(1)]/(1)\times 100\%$	−2·4%	6·4%	−7·5%

polyester laminates of various thicknesses agreed favorably with the experimental data, as shown in Table 1 and Fig. 2. A computational model based on finite-element analysis method developed by Lee and Sun(16) can predict the ballistic limit velocity of the three types of CFRP laminated composites given in Table 2. Table 3 reveals a good agreement between the computed results and experimental data. Sun and Potti(17) showed that the ballistic limit velocities could be predicted reasonably accurately using a simple static energy model. Jenq et al.(19) also predicted the ballistic limit velocity for plain woven glass/epoxy laminates struck by a 14.9 g bullet-like rigid projectile with a tip radius of 5 mm, using finite-element analysis and the principle of conservation of energy. The finite-element analysis method is used to first estimate the velocities when the projectile is about to exit from the distal surface of the target plate. These velocity values are then substituted into the energy balance equation to obtain the residual velocities. Finally, the ballistic limit velocity is obtained by substituting the residual velocities thus obtained into another energy balance equation for the specific impact velocities. Table 4 shows the results for various impact velocities. The mean value of the ballistic limit velocities calculated using the static elastic properties in the finite-element simulations is 116 m/s, which is 24% lower than the value of 153 m/s obtained from the impact test. On the other hand, it is 151.7 m/s if the dynamic elastic modulus is used in the simulations, which is found to be in good agreement with the test result. So, it was concluded that the proposed perforation model was adequate for predicting the ballistic limit velocity of a glass/epoxy laminated plate struck by a bullet-like projectile if the high strain-rate elastic properties of the material were considered. Goldsmith et al.(21) performed an experimental and analytical investigation on the ballistic resistance of woven carbon fiber/epoxy laminated plates perforated by a 60° cylindro-conical hard steel projectile for three sample thicknesses. Figure 3 shows the ballistic limit velocity as a function of the plate thickness, in which the curve is initially concave downward, followed by a linear rise as is also the case for metallic plates struck by a cylindro-conical projectile. A good agreement is found between experimental data and predicted values obtained using almost the same analytical model as used in Refs. (10) and (11). Ballistic limit velocities of carbon and Kevlar fiber laminates are compared in Fig. 4, which indicates that the perforation resistance of carbon fiber laminates of identical thickness is not nearly as good as that of Kevlar laminates. V_{50} is another measure for ballistic limit velocity, which is used throughout the armor industry to compare different armor materials and systems. It is defined as the estimated velocity which gives 50% probability of perforation. Iremonger and Went(22) conducted ballistic tests for nylon 6.6/ethylene vinyl acetate composite laminates struck by a chisel-nosed steel cylinder projectile and measured the V_{50} ballistic limit velocities for four different laminate thicknesses. The test results showed that they were approximated by $V_{50}=K\sqrt{A}$, in which K is a constant depending on the laminate material and the projectile configuration, and A is the areal density (mass per unit area). For

Table 4 Summary of the simulated impact test results

Run no.	Incident velocity (m/sec)	Simulated residual velocity^1 (m/sec)	Predicted ballistic limit^2 (m/sec)	Note
s01	115	34.1	109.8	the static elastic properties were used in the numerical simulations
s02	130	64.4	112.9	
s03	150	96.2	115.0	
s04	170	125.1	115.1	
s05	180	137.2	116.5	
s06	190	148.9	117.9	
s07	200	162.1	118.0	
s08	250	217.9	122.6	
dm01	150	31.6	146.6	the dynamic elastic properties were used in the numerical simulations
dm02	160	61.6	147.7	
dm03	170	79.0	150.5	
dm04	180	97.4	151.4	
dm05	190	112.1	153.4	
dm06	200	128.3	153.4	
dm07	250	192.8	159.1	

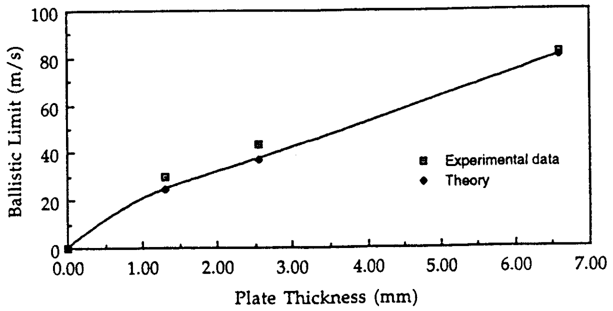

Fig. 3 Ballistic limit as a function of plate thickness for the 12.7-mm-diameter cylindro-conical projectile

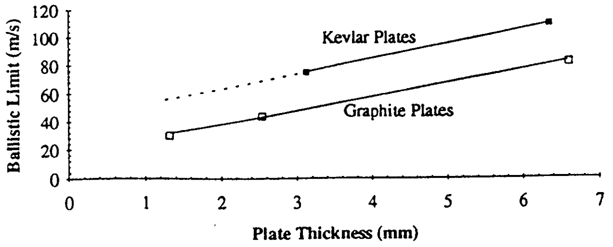

Fig. 4 Comparison of the ballistic limits of Kevlar and graphite laminates

the composite laminates used in their investigation, the value of K was found to vary from around 160 to 190. Kasano and Abe$^{(24)}$ performed high-velocity impact tests on orthotropic and quasi-isotropic CFRP laminates using a steel ball projectile of 5 mm diameter, weighing 0.51 g, and obtained linear relationships between ballistic limit velocity and laminate thickness for both laminates. They also found that the orthotropic laminates had a slightly higher resistance to the ballistic impact than the quasi-isotropic ones of identical thickness.

3.2 Residual velocity

The residual velocity, which is often called final or terminal velocity, is the velocity which is attained

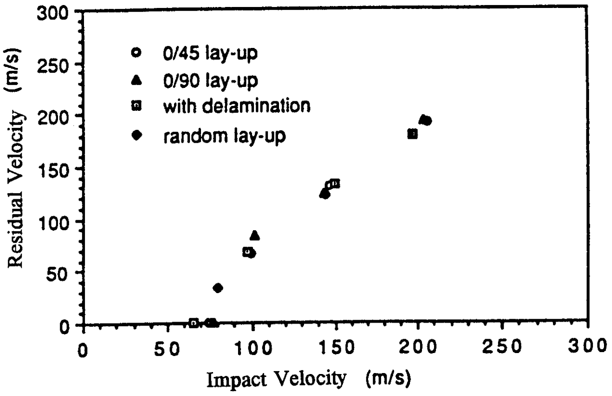

Fig. 5 Residual velocity as a function of impact velocity for the perforation of 5-ply laminates of various constructions by a 60°, 12.7-mm-diameter cylindro-conical projectile

just as a projectile passes through the target plate and exits from it. Experimental results by Zhu et al.$^{(10)}$ showed that the residual velocity increased with increasing impact velocity, and indicated that neither lay-up nor partial delamination played a significant role in the perforation phenomenon of the woven Kevlar/polyester laminates as shown in Fig. 5. The volume fraction of the matrix does not also appear to affect the residual velocity as shown in Fig. 6. Numerical calculations by Zhu et al.$^{(11)}$ showed that the effect of strain rate and in-plane Young's modulus on the residual velocity of Kevlar/polyester laminates was negligible as shown in Figs. 7 and 8, and that the predicted residual velocity was in good agreement with the experimental data. A finite-element model by Lee and Sun$^{(16)}$ was applied to predict the relationship between the impact and residual velocities of the projectile. Good agreement is observed between finite-element analysis predictions and experimental data as shown in Fig. 9 for the type II specimen given in

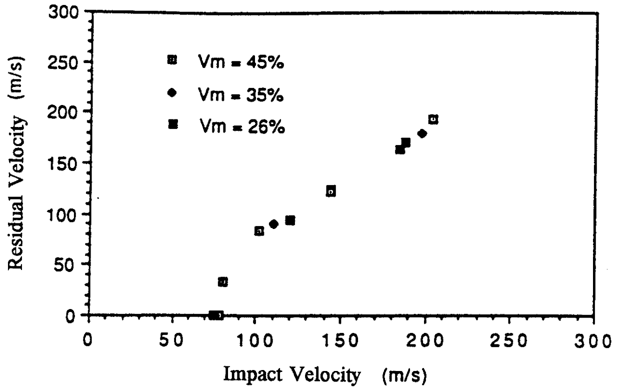

Fig. 6 Effect of matrix volume fraction on the ballistic performance of a 60°, 12.7-mm-diameter projectile striking a 5-ply target

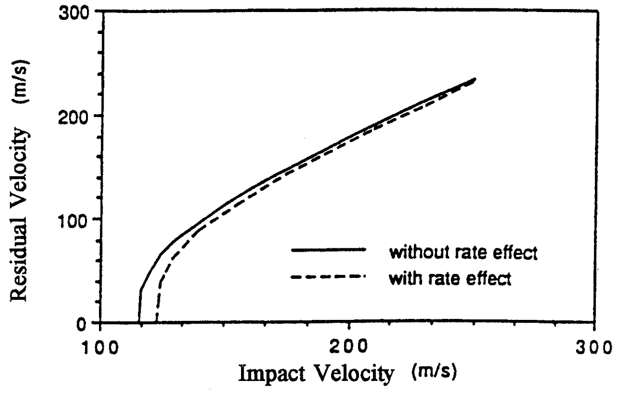

Fig. 7 Comparison of computed residual velocities for a mean indentation pressure based on static values and that increased by 10% to simulate a strain rate effect

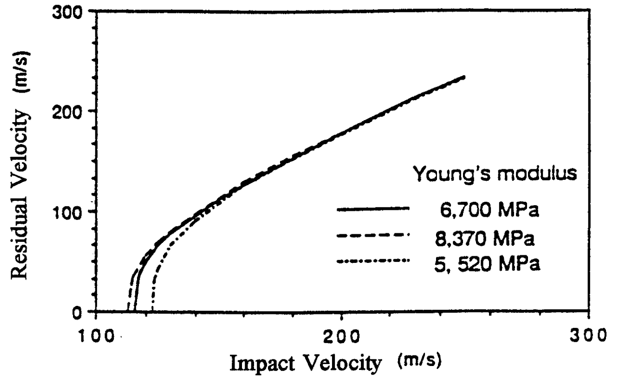

Fig. 8 Sensitivity of the computed residual velocities to the value of the in-plane tensile Young's modulus (a value of 6.7 GPa was used in the general calculations)

Table 2. The figure also shows that the ideal curve represented by $V_R=(V_S^2-V_L^2)^{1/2}$ can be used to predict the perforation characteristics, in which V_R, V_S, and V_L are the residual, impact and ballistic limit velocities, respectively. Sun and Potti(17) proposed a simple static penetration energy model to predict the residual velocities of the projectile perforating the CFRP laminates. The predictions of the residual velocities are close to the experimental results obtained from dynamic tests for the thin laminates as shown in Fig. 10, and they also provide reasonably close estimates for the thicker laminates as shown in Fig. 11. The predicted values provided an upper bound for the experimental values in all the cases in their study. Jenq et al.(19) predicted the residual velocities of a bullet-like projectile perforating plain woven glass/epoxy laminates, using finite-element analysis. Figure 12 shows a plot of the residual velocity versus impact velocity, in which curves A and B correspond, respectively, to the results calculated using the static and the dynamic elastic properties as input data in the finite-element simulations. The trend of the test results represented by the dark squares agrees well with curve B, while a discrepancy exists between the exper-

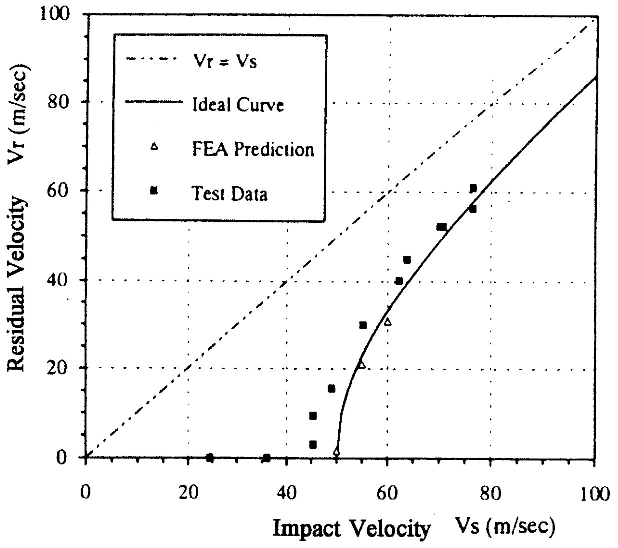

Fig. 9 Comparison of ballistic characteristics for type II laminate

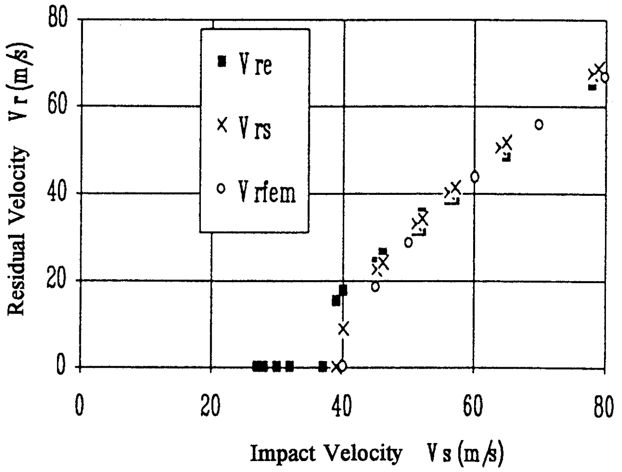

Fig. 10 Residual velocities versus impact velocities for the 2-mm-thick laminates

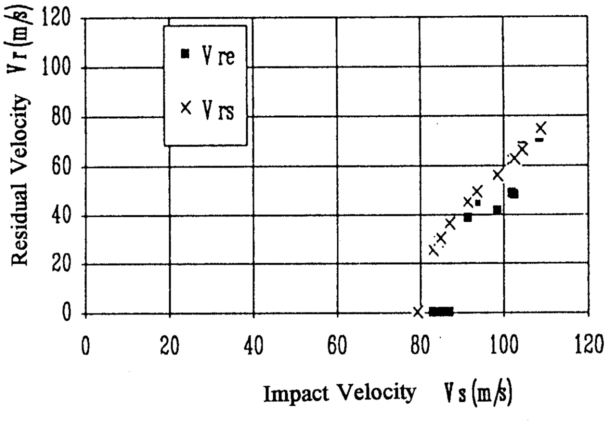

Fig. 11 Residual velocities versus impact velocities for the 6.1-mm-thick laminates

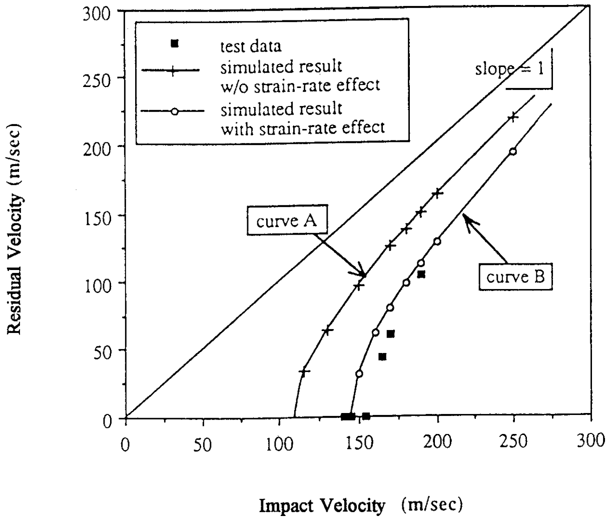

Fig. 12 Residual velocity versus impact velocity

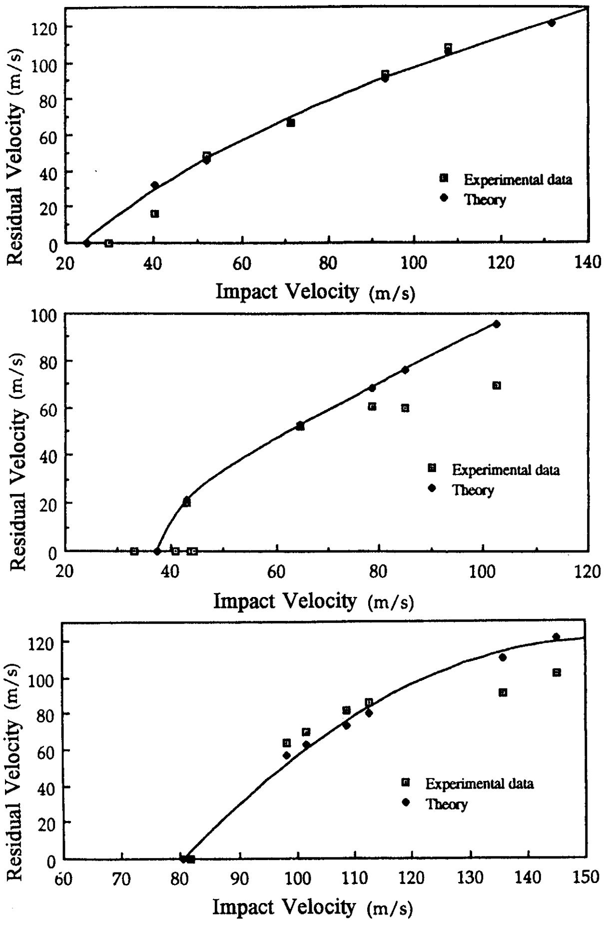

Fig. 13 Residual velocity as a function of impact velocity for samples of three thicknesses upon being struck normally by a 12.7-mm-diameter cylindro-conical projectile

imental trend and curve A due to the strain-rate sensitivity of the glass/epoxy composites. Goldsmith et al.(21) measured the residual velocities of cylindro-conical projectiles perforating woven carbon fiber/epoxy laminates with thicknesses of 1.31, 2.54, and 6.60 mm and plotted them as a function of impact velocity as shown in Fig. 13. The agreement between predicted and measured residual velocities is quite reasonable for the thinnest and thickest plates, but deviates for the intermediate thickness plate at higher impact velocities. The slopes of the linear regions in Fig. 13 are inversely proportional to the plate thickness. Sun and Potti(23) presented a modified simple energy model instead of the static punch-through energy model proposed in Ref. (17). The residual velocities predicted using the modified model compared very well with the experimental results for the CFRP laminates with a quasi-isotropic lay-up struck by a cylindrical projectile with a flat indenting face. They further developed a dynamic response model, in which a circular target plate was discretized using ring elements, and the contact between the projectile and the elements was modeled using contact springs. The new model provided very good predictions of residual velocities for laminated composites of various thicknesses and sizes based on the data from a single static punch test. Figure 14 shows the relationship between residual and impact velocities for CFRP laminates with $([0/90/\pm 45]_s)_6$ lay-up, where the critical deflection criterion was employed. Kasano and Abe(24) compared the residual velocities predicted from the two simple models based on the law of conservation of momentum and/or energy, with the experimental results. Figure 15 shows the residual velocities of the orthotropic CFRP laminates as a function of the impact velocity. A good agreement is found between them, although the experimental data are limited.

3.3 Perforation energy

The perforation energy or perforation threshold energy is defined as the minimum energy required to perforate the target plate. Experimentally, it is determined by measuring the lowest impact velocity

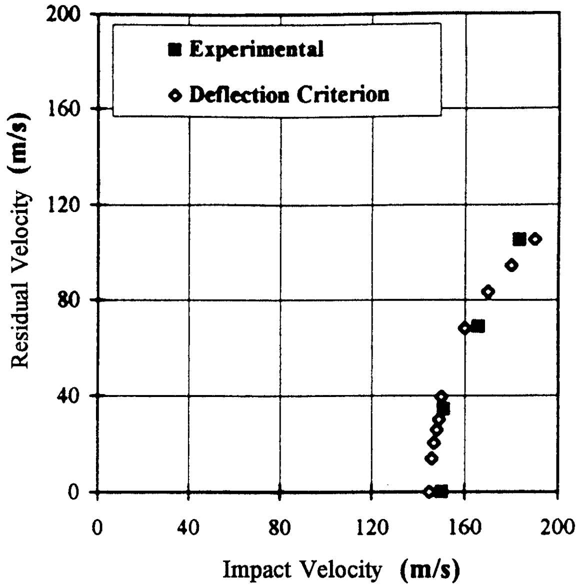

Fig. 14 Residual velocities versus impact velocities for 48 ply $D/d=5$ laminates by projectile 2

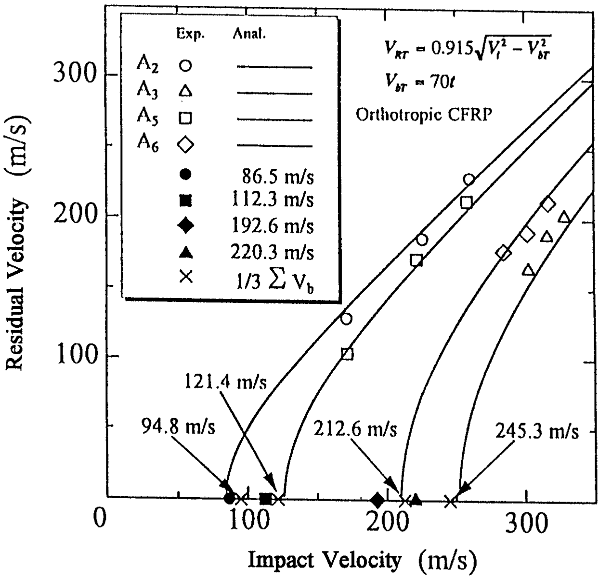

Fig. 15 Residual velocity versus impact velocity for target plate An

required for the projectile to just pass through the plate. The earliest work conducted on GFRP target plates by Gupta and Davis(12) showed a linear relationship between the perforation energy of 0.30-caliber projectiles and the plate thickness as shown in Fig. 16. Cantwell and Morton(13),(14) reported the variation of perforation threshold energy with specimen geometry in a number of CFRP laminates subjected to both low- and high-velocity impact loading. The low-velocity perforation tests, which were conducted using a drop-weight tower with a 680 g-carriage and a 6 mm-diameter hemispherical nose, showed that the perforation energy increased with increasing thickness and length of the beam-like specimens, as shown in Figs. 17 and 18. They also suggested that three major energy-absorbing mechanisms, i.e., elastic deformation, delamination and shear-out, were active during low-velocity impact on CFRP laminates; they then proposed a simple model for predicting the perfora-

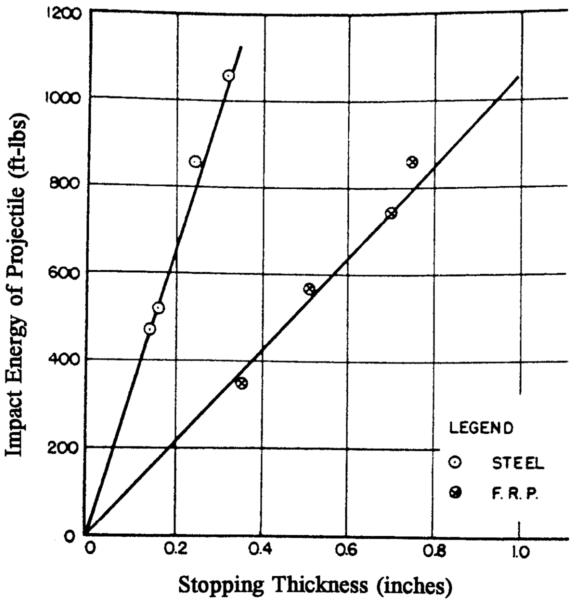

Fig. 16 Impact energy versus stopping thickness for 0.30-caliber projectile

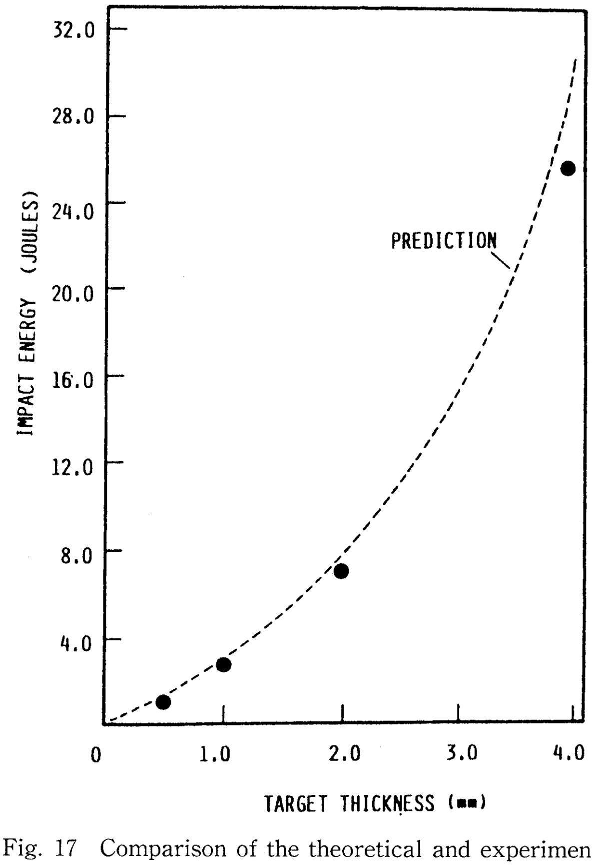

Fig. 17 Comparison of the theoretical and experimental low velocity perforation energies for the (±45°) laminates

Table 5 Comparison of the experimental and predicted perforation threshholds for low-velocity impact loading

Laminate	*Experimental threshold* (*J*)	*Predicted threshold* (*J*)
$(\pm 45^\circ)_s$	1·5	1·3
$((\pm 45^\circ)_2)_s$	3·2	3·7
$((\pm 45^\circ)_4)_s$	7·4	7·8
$((\pm 45^\circ)_8)_s$	25·5	29·9
$(0^\circ_2, \pm 45^\circ)_s$	2·9	3·5
$((0^\circ_2, \pm 45^\circ)_2)_s$	6·6	7·5

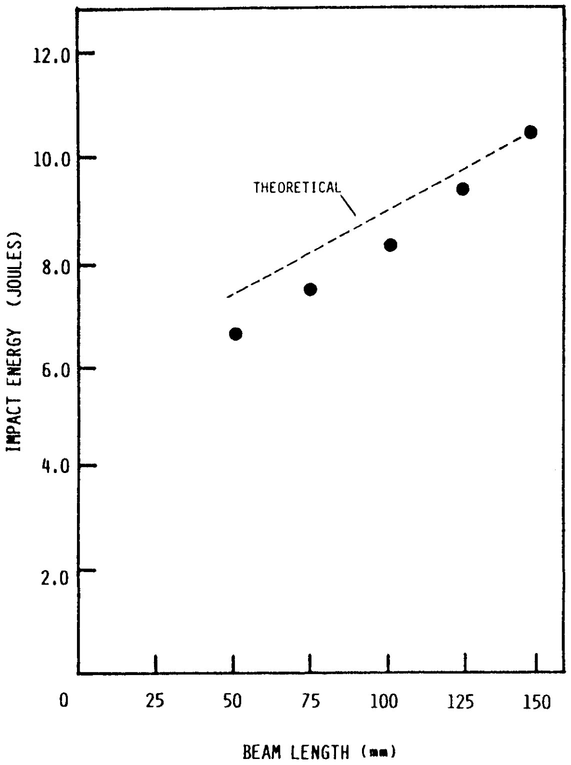

Fig. 18 Comparison of the variation of the theoretical and experimental low-velocity perforation energies for the (0°, ±45°) laminates

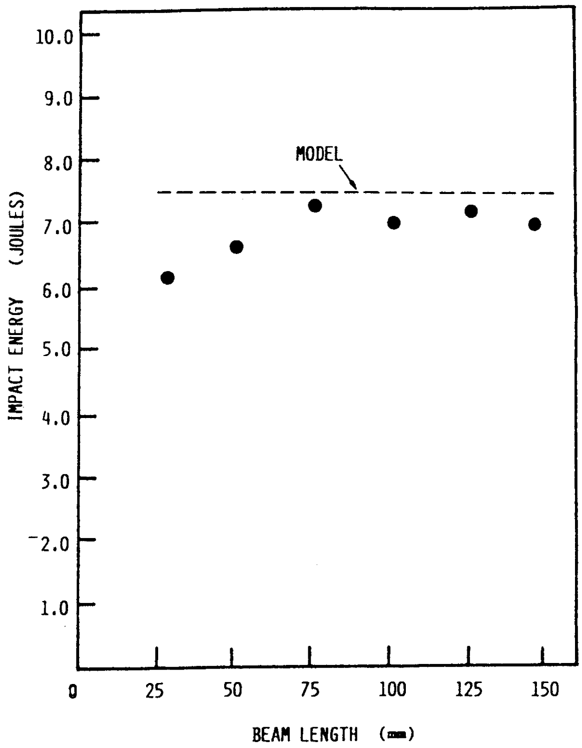

Fig. 19 Comparison of the variation of the theoretical and experimental high-velocity perforation energies with beam length in the (0°, ±45°) laminates

tion energy by examining the mechanisms of penetration and perforation. The model based on the understanding of these mechanisms can predict not only the perforation energy for thinner laminates, but also the effect of beam thickness and length on the perforation energy with reasonable success as shown in Figs. 17 and 18. However, the model is not applicable to thick laminates because it underestimates the experimental perforation energy by a considerable amount as shown in Table 5. On the other hand, high-velocity perforation tests using a nitrogen gas gun with a 6 mm-diameter steel ball showed that the perforation energy did not appear to vary significantly with beam length as shown in Fig. 19. The model was then modified by ignoring the contribution of the elastic deformation energy to the perforation process, and by considering solely delamination and shear-out stages. The modified model again predicted the experimental data with reasonable success and it can be used to successfully predict the perforation energy for the CFRP laminated plates with thickness of up to 4 mm. Wu et al.(18) measured the perforation energy of $(0^\circ_2/90^\circ_2)_S$ E glass/epoxy laminates struck by hemispherically tipped projectiles and found that the perforation energy was more than twice that loaded quasi-statically. Wu et al.(20) also conducted impact tests on woven glass/epoxy laminates using the same setup and procedure as in Ref.(18), and investigated the relationship between the impact energy and the absorbed energy of the projectiles. Figure 20 shows the result, in which the absorbed energy corresponding to the ballistic limit is 38.3 J. The absorbed energy was found to remain approximately constant beyond the ballistic limit, and thus they concluded that the maximum energy which the woven glass/epoxy laminated composites could absorb during impact loading appeared to be at the ballistic limit. In other words, when the impact velocity is higher than the ballistic limit velocity, the energy absorbed by the laminates is not greater than the perforation energy. Goldsmith et al.(21) investigated the perforation energy using the phenomenological model based on the work

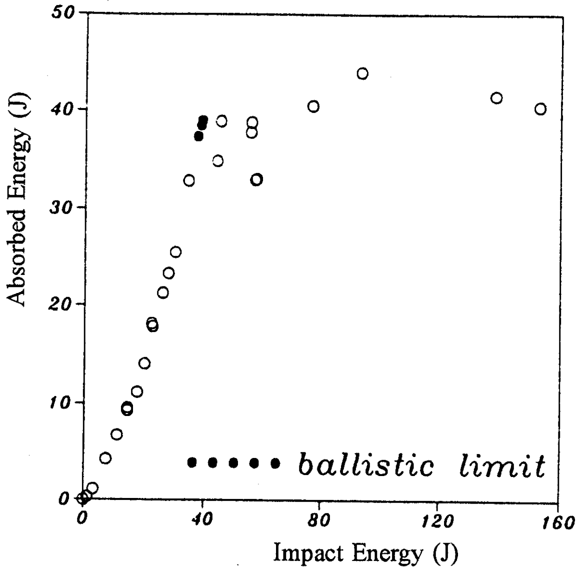

Fig. 20 Relationship between the impact energy and the absorbed energy of the projectiles

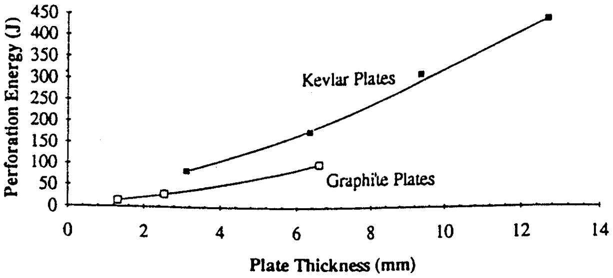

Fig. 21 Comparison of the observed perforation energy at the ballistic limit of Kevlar and graphite composites

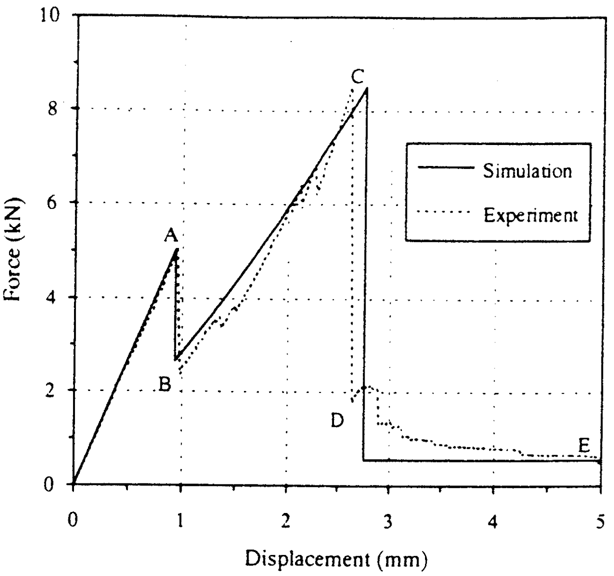

Fig. 22 Simulated static punch curve for type I laminate

done as the result of global plate deflection, the compressive energy dissipated in the creation and relaxation of the conical shaped hole, and the work of friction among other factors. A reasonably good agreement was found between the measured and predicted perforation energy. Comparison of the perforation energy of carbon and Kevlar fiber laminates is shown in Fig. 21, indicating that Kevlar is superior in stopping cylindro-conical projectiles and hence in absorbing more energy. Iremonger et al.(22) reported that there was a trend for use of nylon 6. 6/ethylene vinyl acetate laminates with lower areal density manufactured at a lower pressing load to absorb more impact energy due to the increase in delamination.

4. Understanding of Perforation Process and Mechanisms

Understanding of the perforation process and mechanisms is another subject of interest, which is necessary in order to develop analytical and numerical models for predicting the perforation characteristics. Impact load-deflection history and target plate response such as plate profile and maximum deflection during impact loading provide a better understanding of the perforation process and mechanisms, although the impact perforation is an exceedingly complicated mechanical process. As mentioned in Section 3.3, Cantwell and Morton showed that elastic deformation, delamination and shear-out stages were the major energy-absorbing mechanisms during low-velocity impact on CFRP laminates, and that, for high-velocity impact, the elastic deformation was excluded from these stages. Zhu et al.(10),(11) found that local deformation and fiber failure constituted the major energy absorption mechanisms in the impact perforation on woven Kevlar/polyester laminates, and they characterized the perforation process by three consecutive stages: bulging, delamination and fiber failure. Lee and Sun(15),(16), on the other hand, conducted a series of static punch tests and found that the perforation process of CFRP laminates consisted of three stages: pre-delamination, post-delamination before plugging, and post-plugging. From this finding, they developed a quasi-static computational model based on finite-element analysis to simulate the perforation process of CFRP laminated composites subjected to a blunt-ended punch. Comparison of punch curves showed a good agreement between the test and modeling results as shown in Fig. 22. They also found, from high-velocity impact tests, that the dynamic failure modes were very similar to those of the static case, which indicated the possibility of using the static punch curve to characterize the dynamic perforation process. However, Wu et al.(18) measured the force history of E glass/epoxy laminates struck by hemis-

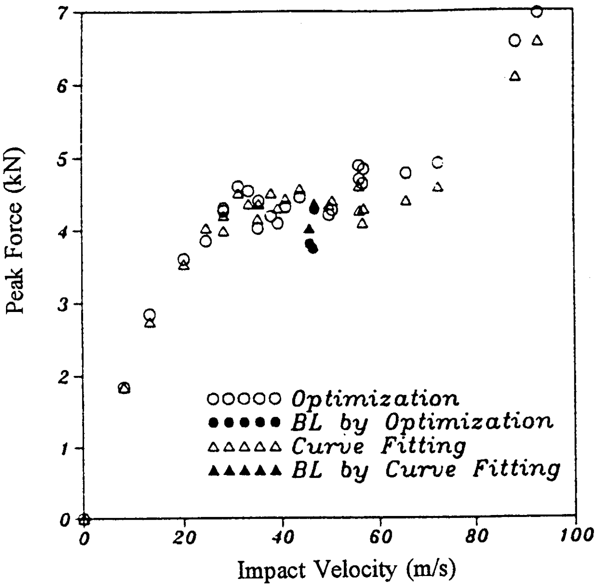

Fig. 23 Peak impact force versus impact velocity of the projectile (*BL* is the ballistic limit)

pherically tipped projectiles, using a newly developed laser Doppler anemometer and they found significant rate effects on the peak impact force and the perforation energy by comparing the results of impact to those under quasi-static loading. Therefore, it was concluded that the results obtained from a quasi-static punch test may not be directly applied to predict the dynamic impact results, which was contrary to the reports of Lee and Sun who dealt with carbon fiber composites. The difference between both conclusions regarding the applicability of a quasi-static punch test may be due to the difference between the strain-rate sensitivities of the materials used. That is, GFRP is a rate-sensitive material, while CFRP is not. Jenq et al.(19) also compared high-velocity impact test results for glass/epoxy woven laminates with those of a quasi-static punch test proposed by Lee and Sun, and they confirmed that, although the major damage pattern found in the impacted specimens was similar to that for the quasi-static perforated specimens, the delamination area of the former case was about nine times greater than that of the latter. Wu et al.(20) measured the impact force-time history when a woven glass/epoxy laminate was struck by a hemispherically tipped projectile, and they obtained the relationship between the peak impact force and the impact velocity as shown in Fig. 23. As the impact velocity increases and approaches the ballistic limit velocity, the incremental rate of the peak impact force is found to be reduced and finally zero when the velocity approaches the ballistic limit velocity. However, when the impact velocity increases beyond the ballistic limit velocity, the peak impact force increases once more. Goldsmith et al.(21) showed that, for cylindro-conical projectile perforation, the crater occurred in the form of a frustrum of a cone, which was similar to the spallation phenomenon common in glass and ceramics subjected to impact load. Iremonger et al.(22) investigated the perforation mechanisms of nylon 6.6 fiber-reinforced ethylene vinyl acetate composite laminates impacted by a chisel-nosed fragment-simulating projectile and they found that the perforation was initiated by two main phases, i.e., shear cutting and tensile failure of the fibers, followed by delaminations between layers and additional tensile failure of the fibers.

5. Conclusions

Early studies of impact perforation of fiber composite laminates are reported in Ref.(25) which focuses exclusively on the residual strength of advanced composite materials and structures perforated by foreign objects. The most recently published book by Abrate(26) refers partly to the ballistic impact on composite laminates. In the present article, recent studies of impact perforation of fiber composite laminates, most of which have been published over the past decade, have been reviewd. Only a limited amount of literature was available for the present review, since the study of impact perforation of composite materials is still in its infancy. These investigations, although few, have compiled our knowledge of the perforation process and mechanisms as well as the perforation characteristics of typical fiber composite laminates such as GFRP, CFRP, and AFRP. In spite of such efforts, the perforation process and mechanisms are, at present, not fully understood because of their complexity due to the number of factors affecting them. A more detailed observation of the ballistic impact phenomenon is required for a better understanding of the perforation process and mechanisms, which will be helpful with analytical and computer modelings for simulating the perforation process and for predicting perforation characteristics. In order to develop a precise model for accurate predictions, more attention should be paid to the perforation process and mechanisms when the impact velocity is very close to and slightly above the ballistic limit, which is associated with the important problem of velocity drop(27),(28).

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