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A NUMERICAL ANALYSIS OF THE BALLISTIC PERFORMANCE OF A 6.35-mm TRANSPARENT POLYCARBONATE PLATE

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D. Nandlall
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December / décembre 1998

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ABSTRACT

Polycarbonate is a lightweight polymer commonly used for transparent armour. In this study, an attempt is made to examine the ballistic performance of a 6.35-mm polycarbonate plate struck by spherical and fragment-simulating projectiles. The ballistic limits of the target plate were obtained for three different sizes of spherical projectiles and two different calibres for the fragment-simulating projectiles. The results obtained showed that, in addition to the mass, the geometry can significantly affect the ballistic performance of a target for these small-calibre projectiles. It was shown that the ballistic limit of the polycarbonate plate was smaller for a spherical projectile than a fragment simulating projectile of an equivalent mass. The crater development and plug formation for both the spherical and fragment-simulating projectiles were examined based on observations of the localisation of the high strain rate region and the distribution of the effective plastic strain. It was found that the mode of plug formation of the two types of projectiles differs significantly. Fragment simulating projectiles created larger plugs.

RÉSUMÉ

Le polycarbonate est un matériau léger utilisé dans les armures transparentes. Dans cette étude, on a étudié le rendement balistique d'une plaque de polycarbonate d'une épaisseur de 6,35 mm frappée par des projectiles sphériques et des fragments simulants. Les limites balistiques de la plaque ont été obtenues pour trois types de projectiles sphériques et deux calibres de fragments simulants. Les résultats obtenus ont montré que la géométrie pourrait avoir un effet considérable sur le rendement balistique de la cible. On a démontré que la limite balistique de la plaque contre un fragment simulant est plus élevée que contre un projectile sphérique de masse équivalente. On a également étudié la formation de cratères et de bouchons en examinant la zone à taux d'écoulement plastique élevé et la distribution de ce dernier. On a découvert que le mode de formation de bouchons pour les deux types de projectiles est différent et qu'un plus grand bouchon s'est formé dans le cas de fragments simulants.

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EXECUTIVE SUMMARY

For personnel protection, acquiring effective transparent armour is a major concern to both the military and the police for tasks such as mine field clearance, bomb disposal and in areas where high optical visibility is required. In these applications the light weight, high optical clarity and high impact resistance materials are required. As a result, glassy thermoplastics, polymers such as polycarbonate and acrylic offer a good choice of material for transparent armour. One of the primary reasons for the high impact resistance of polycarbonate or acrylic is their high ductility, which allows the structures that are made from these materials to undergo large deformation before failure. Another reason is the nonlinear viscoelastic/viscoplastic response, which allows the materials to transform a significant amount of impact energy into heat or internal energy. For these reasons it is important to be able to predict the penetration and high velocity impact response of these materials to design personnel protection systems.

The Defence Research Establishment Valcartier conducted a series of experiments to evaluate the ballistic performance of transparent materials. In this study, numerical techniques were used to examine the deformation process and the penetration of a 6.35-mm polycarbonate plate struck by high velocity small-calibre spherical and fragment simulating projectiles. Three sizes of spheres and two different calibre of fragment simulating projectiles were used in this study. The results obtained show that for these small-calibre projectiles, the geometry, in addition to the mass, has a significant effect on the ballistic performance. The crater development and the plug formation for both the spherical and fragment-simulating projectiles were also examined. It was found that the modes for plug formation of the two types of projectiles differ significantly. In the case of the fragment simulating projectile, larger plugs were created. The crater formation and hole diameter were also examined using the effective plastic strain method.

The results of this study will help to better understand the transient deformation, the penetration and subsequent perforation of transparent materials and will improve DND's capabilities in designing transparent armour systems, particularly given the large amount of resources involved when terminal ballistic experiments are required.

1.0 INTRODUCTION

Effective transparent armour for personnel protection is a major concern to both the military and to police forces for jobs such as mine field clearance, bomb disposal and in areas where high optical visibility is required. Due to the light weight, high optical clarity and high impact resistance of glassy thermoplastics, polymers such as polycarbonate and acrylic offer a good choice of material for transparent armour.

One of the primary reasons for the high impact resistance of polycarbonate or acrylic is their high ductility, which allows the structures that are made from these materials to undergo large deformation before failure. Another reason is the nonlinear viscoelastic/viscoplastic response, which allows the materials to transform a large amount of impact energy into heat or internal energy. The response of these plastic materials are quite difficult to predict mainly because of their viscoelastic/viscoplasticity nature. As pointed out by Frank and Brockman (Ref. 1), a related problem is the uncertainty associated with the material characterisation test results for even moderate strain rates on the order of 10^2 to 10^3 s^{-1}, at which uniform rates are not achievable by conventional tests methods. However, the review by Brockman and Held (Ref. 2) indicates that the state of the art in impact analysis has advanced tremendously during the past years and very large detailed models may now be analysed in a timely fashion, providing much more information to the analyst.

In this present work the approach taken is that it may be possible to use a simple constitutive model to conduct ballistic impact simulations for simple structures. In a study conducted by Chin, Lim and Stillman (Ref. 3), it has been shown that there is a wide variety of material models which can simulate all kinds of complex physics, for which it is impossible to obtain the relevant input data. The approach used in this study consists of adjusting the erosion constant in a simple hydrodynamic elastic/plastic model to obtain a fit over a wide range of projectile types and impact conditions on a polycarbonate plate.

The work presented in this report was performed at DREV between May, 1998 and August, 1998 under Thrust 2FE23, Ballistic Protection and Survivability, Numerical Modelling of Ballistics Events.

2.0 OBJECTIVE

An experimental program is in progress at DREV to study the penetration behaviour of high velocity fragments with masses ranging from 0.1 g to 2.0 g striking polycarbonate targets. The purpose of this experimental investigation is to obtain the ballistic limits of a 6.35-mm polycarbonate plate subjected to impacts by 1.1-g and 0.325-g fragment simulating projectiles (FSPs) and 3-mm, 4.76-mm and 6.35-mm steel spheres.

The primary objective of this work is to use numerical simulation to predict the ballistic limits of the 6.35-mm polycarbonate plate against the projectiles under consideration in the experimental program in an effort to optimise the test procedures and minimise the number of tests required. The area in the target plate that is experiencing large strains and high strain rates is also identified and examined using the effective plastic strain.

3.0 NUMERICAL SIMULATIONS

LS-DYNA2D (Ref. 4), a hydrodynamic finite element computer code, was used to simulate the impact of the steel spheres and FSPs onto the polycarbonate plate to determine the ballistic limit against these projectiles. The LS-DYNA2D hydrocode is an explicit two dimensional lagrangian finite element code used for analysing the large deformation and high strain rate response of inelastic structures.

3.1 Numerical Mesh

To model the impact, penetration and deformation processes occurring when the projectile impacts the polycarbonate plate, and the subsequent deformation of the plate, it is necessary to divide the plate and the projectile into a finite number of regions called elements. The network of elements obtained is called a mesh. The computations are then performed, by solving the constitutive equations that describe the relationship between the forces and the displacements in the materials.

In the case of the FSPs, an equivalent axisymmetric FSP was used to represent the standard non-axisymmetric FSP. Nandlall (Ref. 5) in a recent study showed that by conserving the bevel angle of the actual non-axisymmetric FSP, an equivalent axisymmetric FSP could be used to conduct less CPU intensive 2D axisymmetric penetration analyses for relatively thick plates without compromising the predicted ballistic limit.

Figure 1 shows an example of the initial global finite element mesh that was used for the simulations. This mesh was considered as the initial state just as the projectile impacts the target. Due to the axisymmetric nature of the problem studied, only half of the domain was considered. 4-node quadrilateral elements were used through the mesh.

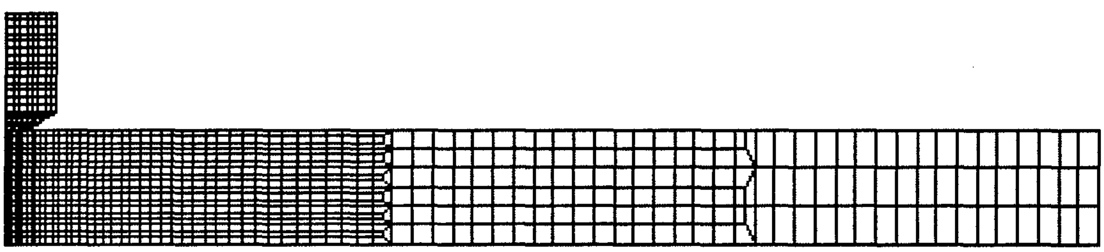


FIGURE 1 - Typical Finite Element Mesh of Projectile/Target System

Table I below shows the element distribution for the different projectile/target systems that were considered in this study:

TABLE I

Element distribution for various projectile/target system

Projectile Type	Number of Elements		Total Number of Elements
	Projectile	Target	
1.100-g FSP	152	906	1058
0.325-g FSP	78	1176	1254
0.110-g Steel Sphere	150	906	1056
0.439-g Steel Sphere	384	906	1290
1.044-g Steel Sphere	486	906	1392

In order to conduct a realistic simulation of the impact problem, the finite element mesh needs to be relatively dense in regions that will experience high stress gradients and large deformations. However, as shown in Fig. 1, a relatively coarse mesh was constructed at the outer regions of the geometry, far from the impact zone, in order to minimise the computational time which could otherwise be extremely large. For this study, a simple mesh sensitivity analysis was conducted. The mesh size was adjusted until the penetration results did not vary as the mesh density was changed. The result was an optimum mesh size that was subsequently used for all the simulations performed in this study.

3.2 Material Models

As discussed in the introduction, the approach used in this study consists of adjusting the erosion constant in a simple constitutive model to obtain a fit over a wide range of projectile types and impact conditions against a polycarbonate plate. The polycarbonate was modelled using a kinematic/isotropic elastic-plastic constitutive model. The model assumes a bi-linear stress-strain behaviour of the material while the strain rate is accounted for very simplistically through a scaling factor applied to the yield stress. Pageau, Nandlall et'al (Ref. 6) conducted an extensive experimental and numerical analysis of cylindrical polycarbonate projectiles striking steel plates and have shown that by adjusting the erosion strain of the polycarbonate material the elastic/plastic constitutive model was capable of reproducing the experimental results quite accurately. In this study a rigid body model was used for the steel projectiles which were not expected to deform during penetration into a polycarbonate target. The parameters used for both the projectile and the target are given in Table II.

For all the material models used in this study, the frictional forces between the materials in contact are not modelled. It was assumed that, for the polycarbonate material, the hydrodynamic pressure dominates the effects of the other forces during the penetration process and, therefore, the frictional forces between the projectile and target are negligible.

TABLE II

Material properties used for LSDYNA2D model

Polycarbonate Plate	FSP, Steel sphere
$\rho = 1.19\ g/cm^3$	$\rho = 7.8\ g/cm^3$
$E = 0.02170$ Mbars	$E = 2.2$ Mbars
$\nu = 0.4$	$\nu = 0.3$
$\sigma_y = 1.345*10^{-3}$ Mbars	
$E_t = 0.68563*10^{-3}$ Mbars	
$F_s = 1.2$	

3.3 Ballistic Performance Evaluation

The procedure used in this study to evaluate the ballistic performance of the polycarbonate plate against the various types of projectiles is called the ballistic limit method. The ballistic limit is defined as the minimum striking velocity which is required to completely perforate a target. This limit is sometimes called the V_{100} limit which, in experimental terms, is the minimum striking velocity at which the projectile will always perforate the target.

The technique used to obtain the ballistic limit is to first conduct a simulation of the projectile at a striking velocity high enough to completely perforate the target. The residual velocity of the projectile after the target has been perforated is then measured. This procedure is repeated, decreasing the striking velocity until the target is no longer perforated. The striking velocities are then plotted against the corresponding residual velocities. A curve fitting routine was applied to fit the data points to the Lambert/Jonas ballistic equation (Ref. 6) given as

$$V_r = \alpha[(V_s)^p - (V_{100})^p]^{1/p} \qquad [1]$$

where V_r and V_s are the projectile residual and striking velocities, respectively. α and p are numerical constants that determine the fit of the equation to numerical data. The striking velocity at which the numerical fit produces a zero residual velocity is then taken as the ballistic limit or V_{100}. This method is described in detail by Zukas (Ref. 7).

4.0 COMPUTATIONAL RESULTS AND DISCUSSIONS

Simulations were performed for two different kinds of projectiles: spheres and fragment simulating projectiles. For the spherical steel projectiles, 3-mm (0.11-g), 4.76-mm (0.439-g) and 6.35-mm (1.044-g) diameter sizes were used while for the fragment simulating projectiles 1.1-g and 0.325-g masses were used. For all the simulations the target was a 6.35-mm thick polycarbonate plate.

Figures 2 and 3 show, respectively, examples of typical simulations that were performed in an effort to obtain the ballistic limit of the polycarbonate plate against the FSP and the spherical projectiles.

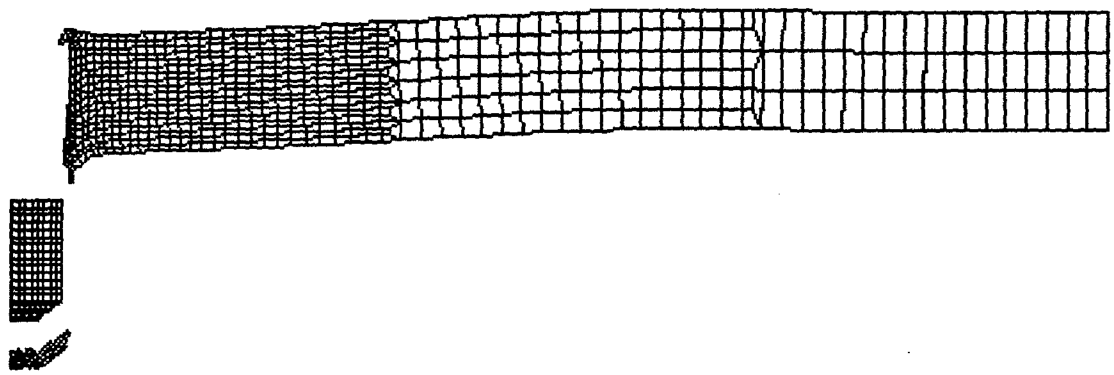


FIGURE 2 - 1.1-g FSP perforating a 6.35-mm polycarbonate plate (V_i=355 m/s).

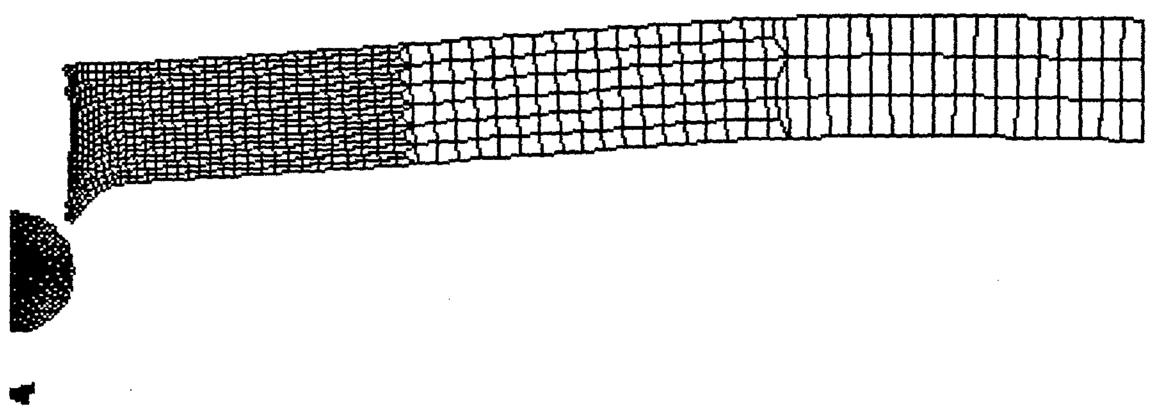


FIGURE 3 - 6.35-mm steel sphere perforating 6.35-mm polycarbonate plate, (V_i=355 m/s).

Figure 4 shows the ballistic limit curves obtained for the 3-mm, 4.75-mm and 6.35-mm spherical steel projectiles whereas Fig. 5 shows the ballistic limit curves obtained for the 0.325-g and 1.1-g FSPs. Table III gives a summary of the all the ballistic limits obtained from Figures 4 and 5. As expected, the ballistic limit for the steel spheres is lowest for the projectile with the highest mass. The same trend is also seen for the FSPs. However, when the FSPs are compared to the steel spheres it can be observed that the ballistic limit for the 1.1-g FSP is 298 m/s, which is lower than the V_{100} for the 4.76-mm steel sphere even though the masses of the two projectiles are approximately the same. This implies that the geometry of the projectile plays an important role in determining the ballistic performance of targets of the type considered in this study.

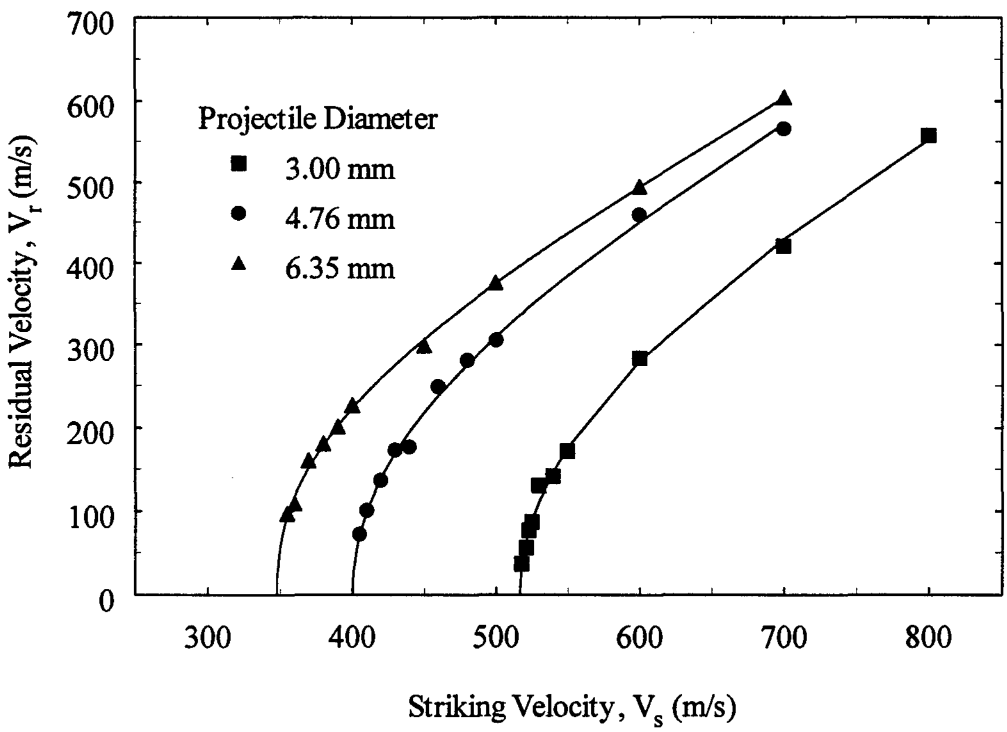


FIGURE 4 - Ballistic limit curves for spherical projectiles striking a 6.35-mm polycarbonate plate

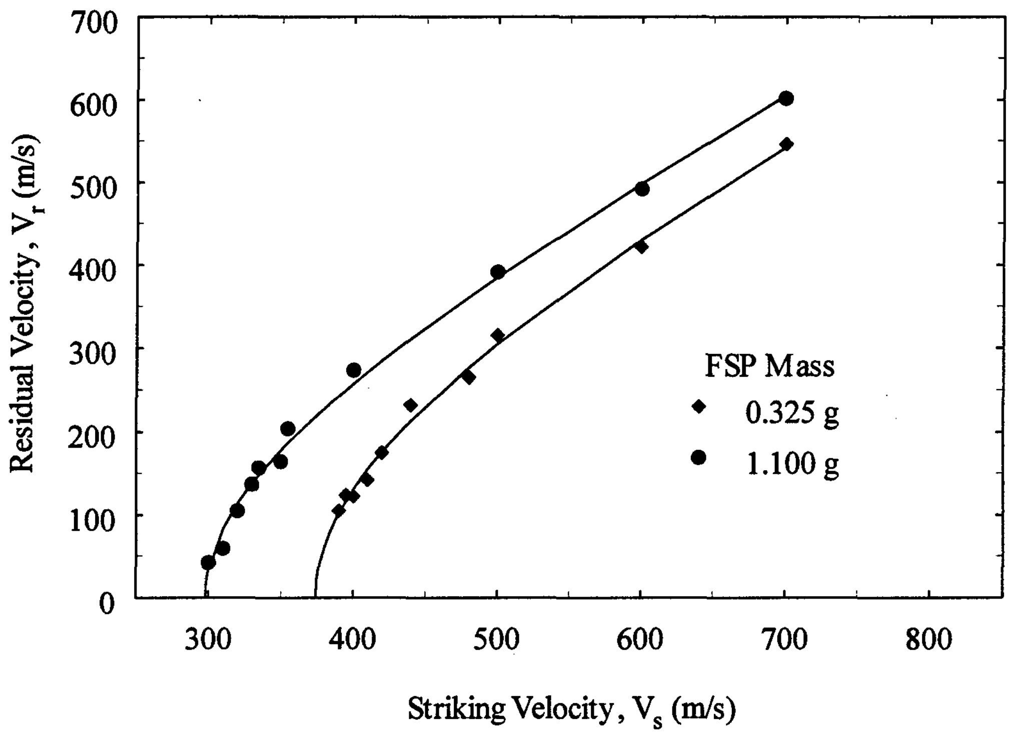


FIGURE 5 - Ballistic limit curves for FSPs striking a 6.35-mm polycarbonate plate.

TABLE III

Ballistic limits of 6.35-mm polycarbonate plate for various projectiles

Projectile	Ballistic Limit (m/s)
0.110-g Steel Sphere (3 mm)	516.8
0.439-g Steel Sphere (4.76 mm)	400.4
1.044-g Steel Sphere (6.35 mm)	347.8
0.325-g FSP	374.2
1.1-g FSP	297.8

Figures 6 and 7 show, for the 1.1-g FSP and 1.044-g (6.35-mm) sphere respectively, the variation of projectile velocity as a function of time for various striking velocities. Careful observation of the curves shown in these figures reveals that there is a

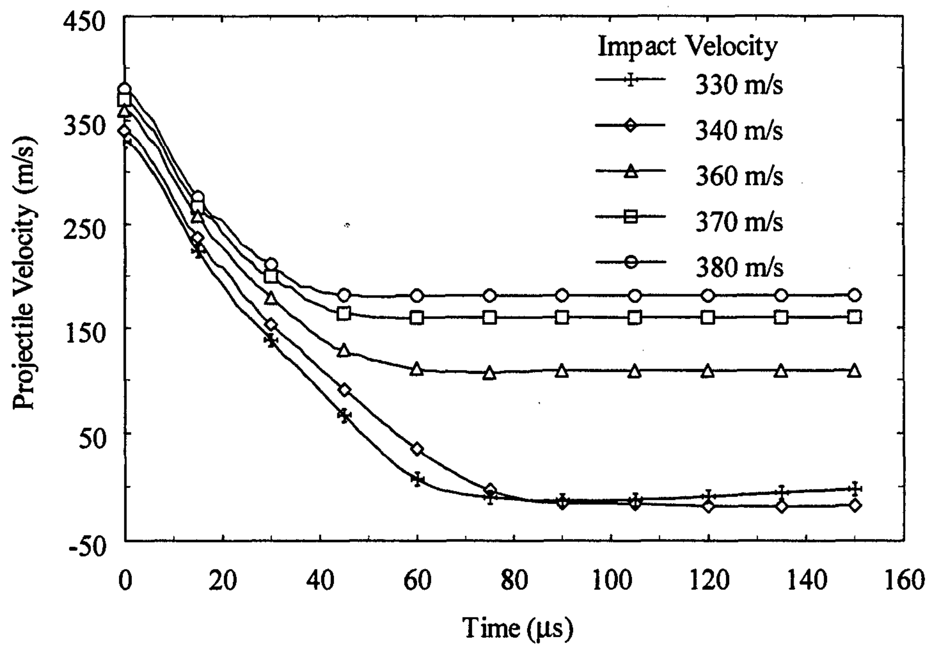


FIGURE 6 - Axial velocity as a function of time for various striking velocities of a 6.35-mm diameter steel sphere on a 6.35-mm polycarbonate plate.

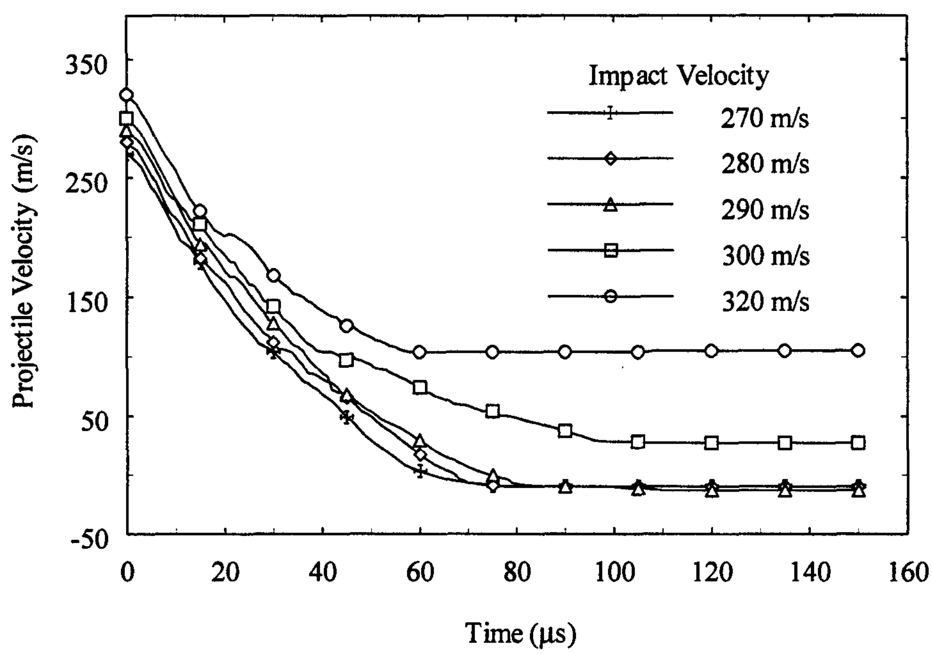


FIGURE 7 - Axial velocity as a function of time for various striking velocities of a 1.1-g FSP on a 6.35-mm polycarbonate plate.

time period during which the projectile stays at the bottom of the crater before rebounding. As the striking velocity approaches the ballistic limit the rest time of the projectile is the longest. As the striking velocity drops below the ballistic limit the projectile does not stay as long at the crater bottom before it starts to rebound. This effect presents another possible method of observing and characterising the ballistic limit.

Figures 8 and 9 show again, for the 1.1-g FSP and 1.044-g (6.35-mm) sphere respectively, the variation of projectile displacement as a function of time for various striking velocities. The displacement was plotted for a point near the centre of each of the projectiles. As in Figs. 6 and 7, it is possible to observe the rest time effect of the projectile. However, in this case the effect of the rest time is not as obvious as in Figs. 6 and 7.

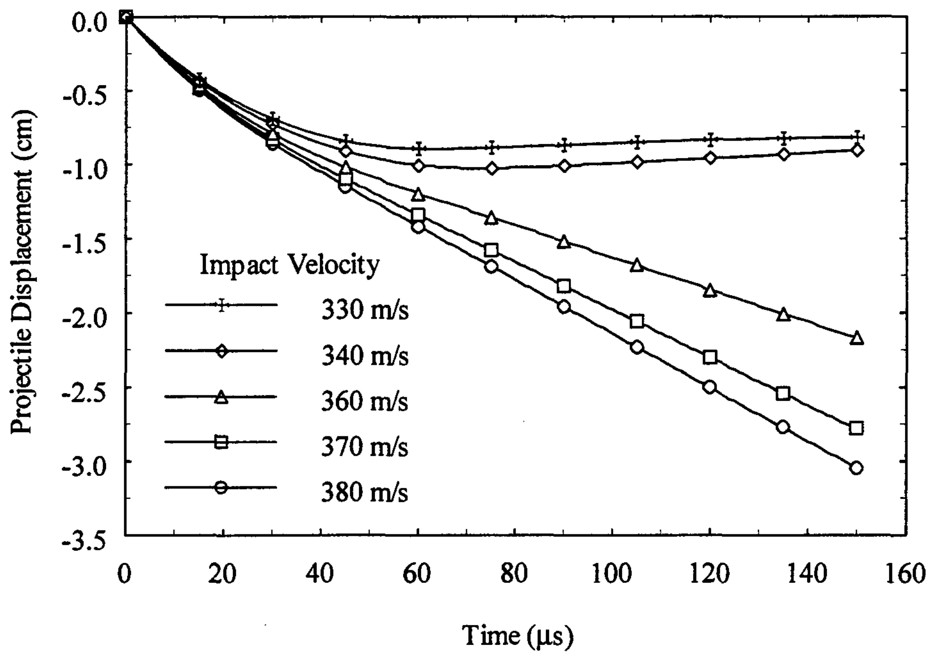


FIGURE 8 - Displacement as a function of time for various striking velocities of a 6.35-mm diameter steel sphere. on a 6.35-mm polycarbonate plate.

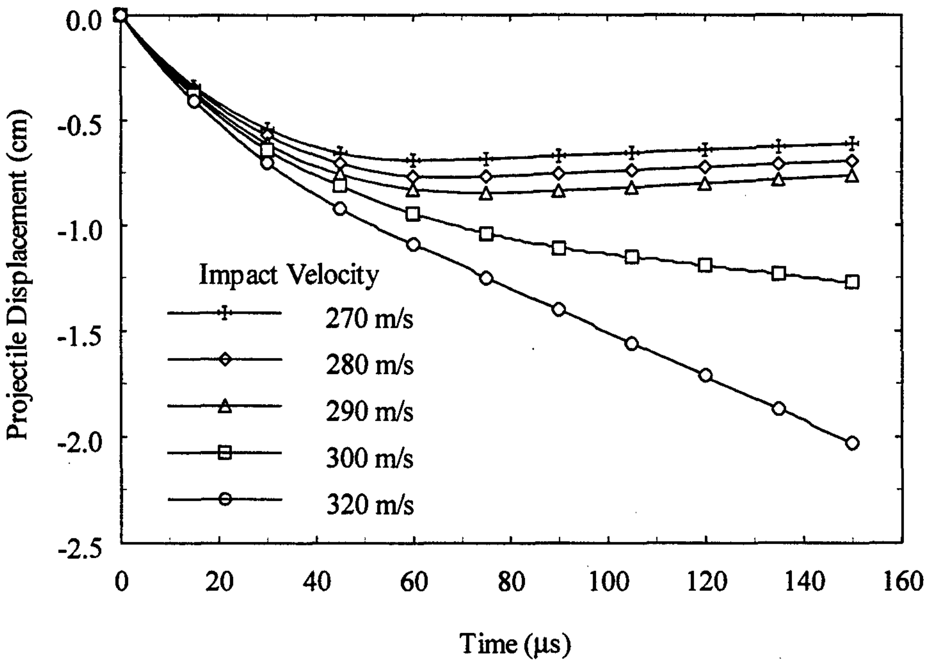


FIGURE 9 - Displacement as a function of time for various striking velocities of a 1.1-g FSP on a 6.35-mm polycarbonate plate.

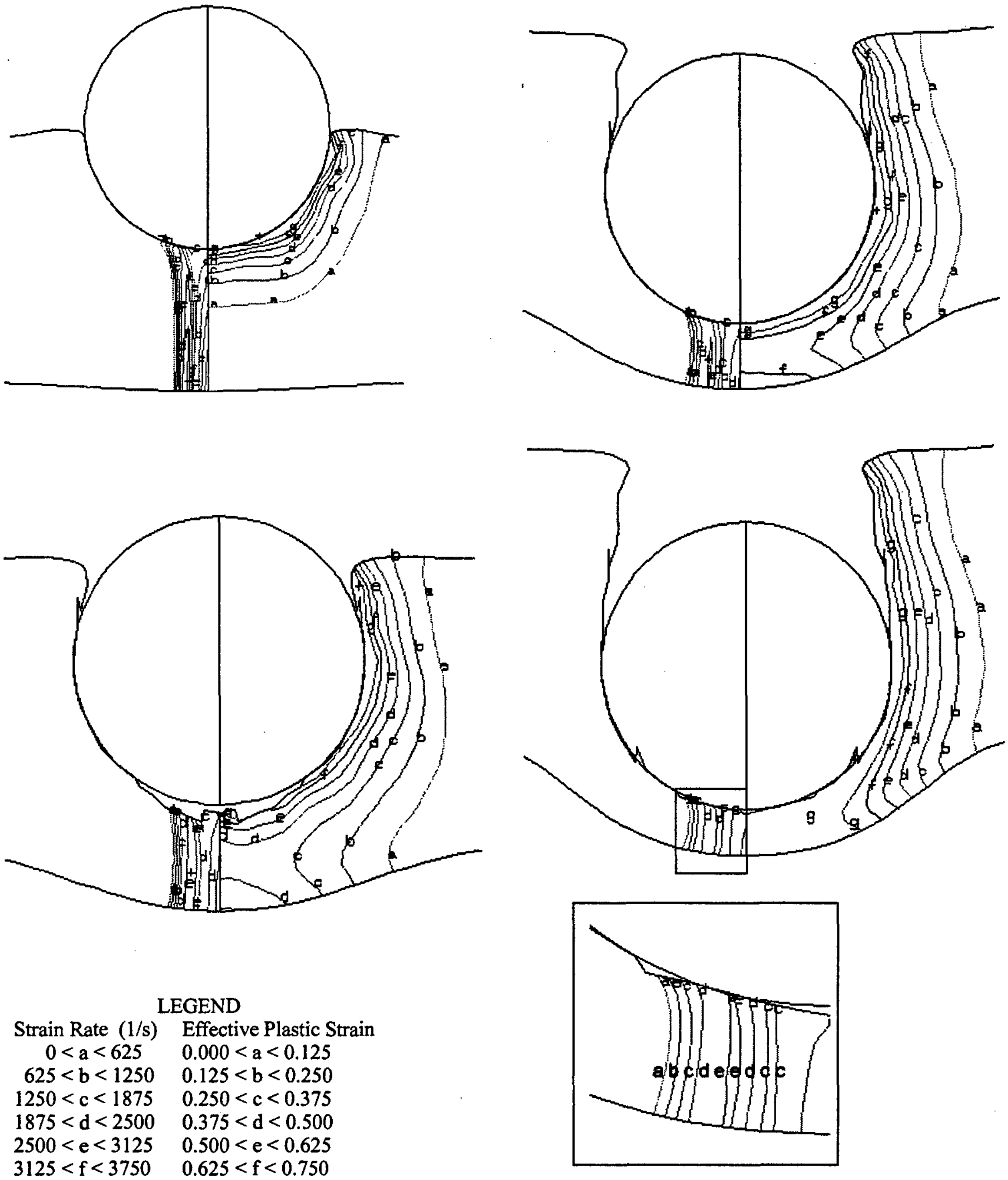
Figures 10 and 11 show, for the 1.044-g (6.35-mm) spherical projectile and 1.1-g FSP respectively, the strains and strain rates that occur within the polycarbonate plate at 10-, 20-, 30- and 40-μs into the penetration event. The striking velocity was 355 m/s for both the 1.044-g steel sphere and the 1.1-g FSP. In both cases, the impact of the projectile induces a bending moment in the area of impact. As the projectile penetrates the polycarbonate plate the material ahead of the projectile continues to be compressed until the stresses in the region exceed the yield strength. When this occurs, the polycarbonate deforms plastically. The stresses continue to increase until the polycarbonate fails along a shear plane at the outer diameter of the projectile. The highest strains are located in a narrow zone at the projectile/crater interface. The thickness of the region of plastic deformation is approximately 1/4 of the diameter of the projectile. It was also observed that the area of the plate with the highest strain rates is located just ahead of the projectile. Careful observation of this high strain rate area, as shown by the insets in Figs. 10 and 11, reveals that the highest strain rates are located away from the central axis. The highest strain rate was of the order of 5000 s^{-1}.

As can also be seen in Figs. 2 and 3 presented above, the process of plug formation for the FSP and sphere were different. The FSP produces a larger plug than the steel sphere. This was mainly due to the area of localisation of the large strains and the flow of target material around the projectile as it approaches the backface of the target.

In the case of the spheres, as the projectile penetrates the plate its curved side tends to push the material outwards and around the projectile. This has two major effects. The first is that the hole diameter in the target plate is smaller than the diameter of the projectile. The second effect is that there is less material in front of the steel sphere to become a plug when the projectile reaches the back face of the plate. It was observed that in the case of the spherical projectile, the plug is formed as the target plate stretches and breaks near the bottom of the crater resulting in a relatively small plug.

In the case of the FSP, the tip has a flat blunt area on the leading edge that compresses the material ahead of the projectile but does not push it aside. The bevel causes some material to move to the side but unlike the case of the sphere there is not a smooth transition from the bevelled side to the outer side of the projectile. This leads to failure in the plate at the point where these two sides meet. As can be seen in Fig. 11, as the plug is formed the plate stretches along the bevelled side of the projectile and breaks near the interface of the bevelled side and the outer side resulting in a large plug. Note that the diameter of the hole in the target plate is approximately the same as the diameter of the FSP.

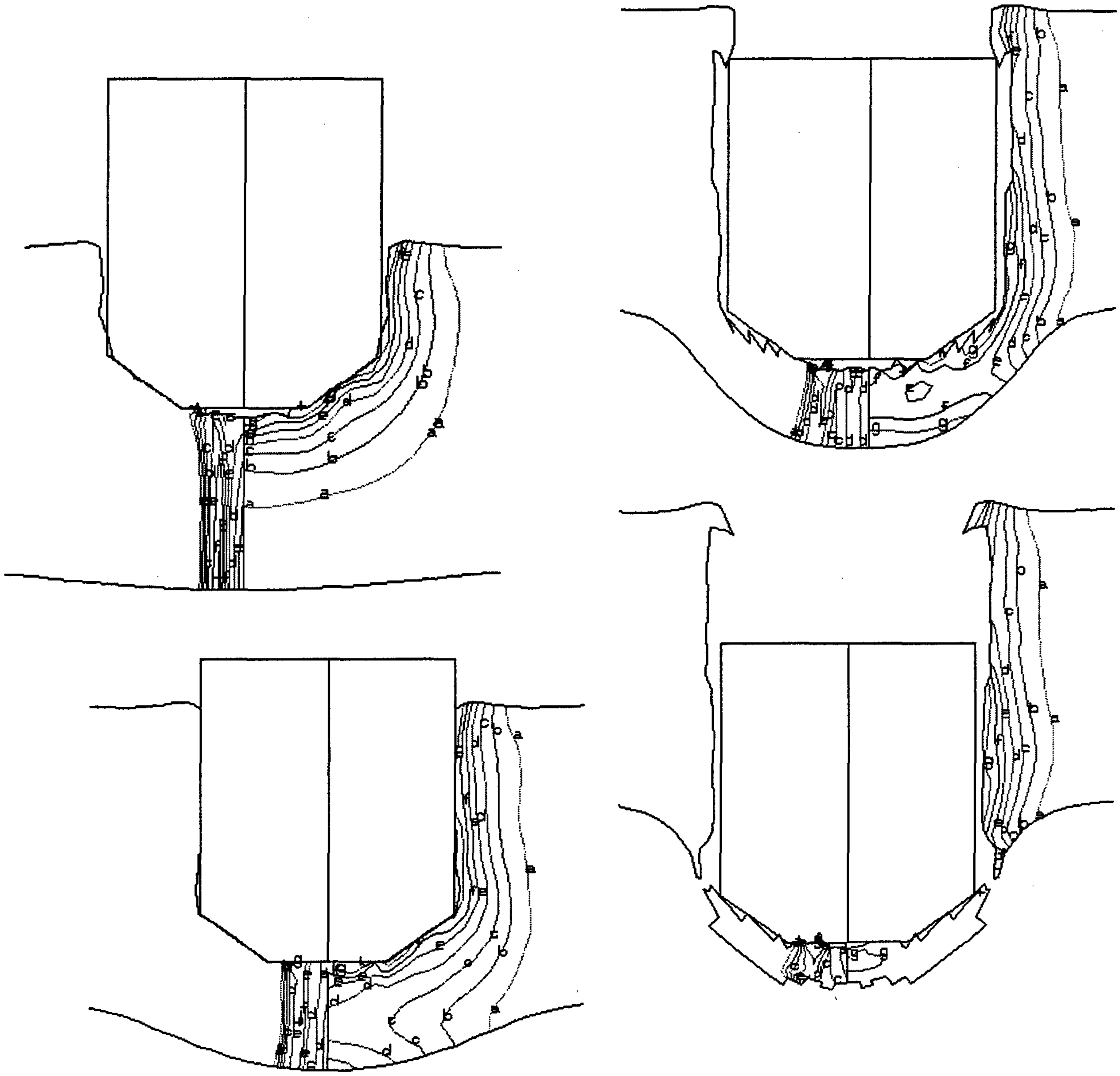
Finally, close observation of Figs. 10 and 11 shows that the time required for the plug to form in the case of the spherical projectile is different than that for the FSP. In the case of the FSP at 40 μs into the penetration event, the plug was already formed whereas in the case of the sphere at 40 μs the plug formation has not as yet started to appear.



LEGEND

Strain Rate (1/s)	Effective Plastic Strain
0 < a < 625	0.000 < a < 0.125
625 < b < 1250	0.125 < b < 0.250
1250 < c < 1875	0.250 < c < 0.375
1875 < d < 2500	0.375 < d < 0.500
2500 < e < 3125	0.500 < e < 0.625
3125 < f < 3750	0.625 < f < 0.750
3750 < g < 4375	0.750 < g < 0.875
4375 < h < 5000	0.875 < h < 1.000

FIGURE 10 - Contours of effective plastic strain (right side) and effective strain rate (left side), for a 6.35-mm (1.044-g) diameter steel sphere striking a 6.35-mm polycarbonate plate with an initial velocity of 355 m/s (a) 10 μs, (b) 20 μs, (c) 30 μs, (d) 40 μs



LEGEND

Strain Rate (1/s)	Effective Plastic Strain
0 < a < 625	0.000 < a < 0.125
625 < b < 1250	0.125 < b < 0.250
1250 < c < 1875	0.250 < c < 0.375
1875 < d < 2500	0.375 < d < 0.500
2500 < e < 3125	0.500 < e < 0.625
3125 < f < 3750	0.625 < f < 0.750
3750 < g < 4375	0.750 < g < 0.875
4375 < h < 5000	0.875 < h < 1.000

FIGURE 11- Contours of effective plastic strain (right side) and effective strain rate (left side), for a 1.1-g FSP striking a 6.35-mm polycarbonate plate with an initial velocity of 355 m/s (a) 10 μs, (b) 20 μs, (c) 30 μs, (d) 40 μs

5.0 CONCLUSIONS

Polycarbonate is a lightweight polymer commonly used for transparent armour. In this study the ballistic performance of a 6.35-mm polycarbonate plate struck by spherical and fragment simulating projectiles is simulated using a hydrodynamic code. The approach used in this study consists of adjusting tuning constants in a simple hydrodynamic elastic/plastic model. This model can be used to evaluate the ballistic performance of a polycarbonate plate against a wide range of impact conditions and projectile types.

The ballistic limits of the target plate were obtained for three different sizes of spherical projectiles and two different calibre for the fragment simulating projectiles. The results obtained showed that in addition to the mass, the geometry affects the ballistic performance for these small-calibre projectiles. It was shown that ballistic limit of the polycarbonate plate was lower for a spherical projectile than for a fragment simulating projectile of equivalent mass. The crater development and the plug formation for both the spherical and fragment simulating projectiles were examined using the localisation of the high strain rate region and the distribution of the effective plastic strain. It was found that the plug formation mode of the two types of projectiles differs significantly resulting in a larger plug formation in the case of the fragment simulating projectile.

6.0 ACKNOWLEDGEMENTS

Special thanks are addressed to Dr. Kevin Williams, Dr. Frank Wong and Mr. Richard Delagrave for the many useful and stimulating discussions with regard to the numerical simulations performed, as well as for the revision of this document. Special thanks are also extended to Mr. Benoit St-Jean and Ms. Gloria Wong for their help in the preparation of this report.

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Polycarbonate is a lightweight polymer commonly used for transparent armour. In this study, an attempt is made to examine the ballistic performance of a 6.35-mm polycarbonate plate struck by spherical and fragment simulating projectiles. The ballistic limits of the target plate were obtained for three different sizes of spherical projectiles and two different calibres for the fragment simulating projectiles. The results obtained showed that, in addition to the mass, the geometry can significantly affect the ballistic performance of a target for these small calibre projectiles. It was shown that the ballistic limit of the polycarbonate plate was smaller for a spherical projectile than a fragment simulating projectile of an equivalent mass. The crater development and plug formation for both the spherical and fragment simulating projectiles were examined based on observations of the localisation of the high strain rate region and the distribution of the effective plastic strain. It was found that the mode of plug formation of the two types of projectiles differs significantly. Fragment simulating projectiles create larger plugs..

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