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An efficient method for continuous measurement of projectile motion in ballistic impact experiments

Darlene Starratt, Tim Sanders, Elvis Cepuš, Anoush Poursartip, Reza Vaziri*

Composites Group, Departments of Metals and Materials Engineering and Civil Engineering, The University of British Columbia, Vancouver, British Columbia, V6T 1Z4, Canada

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Abstract

This paper provides a description of a simple and cost-effective continuous measurement system for impact. Originally developed at Johns Hopkins university for use in flyer plate impact experiments, the measurement system has been enhanced for the continuous, non-contact measurement of projectile displacement during ballistic impact events. A sheet of laser light is progressively blocked and unblocked by the projectile, and the corresponding change in total intensity is measured and converted to a displacement–time curve. Through the use of simple mathematical operations, the system can be used to determine the time histories of projectile velocity and acceleration, impact force and projectile energy loss during an impact event. While this technique can be applied to a wide range of engineering materials, this paper presents examples of measurement results for impact of composite and textile targets. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Continuous measurement; Ballistic impact; Composite materials

1. Introduction

The use of advanced composite materials in applications involving impact by foreign objects has been steadily increasing. The velocities involved with these types of impact event cover a wide range. Low-velocity impacts, on the order of 1 m/s, represent a tool being dropped on a composite structure. Intermediate velocities, in the range of 10–100 m/s, represent runway debris striking an airplane. Ballistic (high velocity) impacts, in the velocity range of 100–1000 m/s, represent the

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* Corresponding author. Tel.: 00-1-604-822-2800; fax: 00-1-604-822-6901.
E-mail address: reza.vaziri@ubc.ca (R. Vaziri)

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impact of bullets, fragments and other low-mass projectiles on composite and textile protective armours or structures. It should be noted that the above definitions for the different velocity regimes are specifically for composite and soft armour materials, and do not necessarily apply to the impact of more traditional metallic targets. A more general classification of velocity regimes is provided by Zukas [1].

Low-velocity, high-mass impacts are often simulated in the laboratory using a drop weight impact tester. This type of instrument drops an impactor of known mass from a known height onto a target. The impactor mass and drop height are varied to obtain the desired impact energy. At such low impact velocities, the impactor force–time history is easily obtained from an attached force transducer. Intermediate-velocity impacts are often performed with the use of a gas gun [2]. Compressed air is used to propel a low-mass projectile down the barrel of the gun. Varying the air pressure controls the initial velocity of the projectile. The motion of the projectile can be measured by a technique similar to that used with the drop weight impact tester, but the complexity involved with measurement of the projectile motion increases with the velocity. Ballistic impact events are commonly performed using a powder gun. This instrument is similar to a gas gun, but makes use of gun powder to propel a low-mass projectile down the gun barrel. The projectiles used with the powder gun are propelled out of the gun muzzle before impacting the target. Due to instability issues associated with these "free-flying" projectiles, and the much higher velocities encountered in the ballistic impact regime, measurement of projectile motion is quite complex.

Despite the complexity involved in obtaining measurements at velocities in the intermediate range and above, there is great interest in being able to determine effectively and efficiently the impact response of the materials used in these velocity regimes. Ideally, one would like to be able to continuously measure the projectile displacement or velocity (and hence determine the energy and force) during an impact event. Until recently, however, this has been quite difficult and expensive to do. It is much easier to obtain "before and after" impact data, such as the projectile impact velocity, v_s, and the projectile residual velocity, v_r.

2. Current measurement methods

The importance of taking measurements during an impact event is evident from the vast amount of work performed in this area. Many different measurement techniques have been used, however, the purpose of this section is to provide an overview of some typical measurement methods, rather than an exhaustive review of the literature.

The majority of the measurement systems available today are limited to taking instantaneous, or discrete, velocity measurements during impact events. Some typical systems include high-speed photography [3], chronographs and optical sensors. Optical sensors and chronographs appear to be the most commonly used devices for measuring impact velocity [4–6]. With these measurement systems, the velocity is calculated from the known distance between two sensors divided by the time taken for the projectile to travel between the two sensors. The sensors that are usually used are either light emitting diodes (LEDs), laser beams [4] or thin wires [7].

Another discrete measurement method, similar in concept to the optical sensor, is the micro-velocity sensor developed by Zee et al. [8]. This method works on the basis of an induced current generated in a coil due to the passage of a magnet. The sensor used by Zee et al. consisted of 11 coils spaced a distance of 2.5 mm (0.1″) apart. The projectile used with this sensor has a magnet attached to its back end. During impact and penetration, the magnet on the projectile induces signals in the coils in succession as a result of the rapidly changing magnetic flux that each individual coil experiences. These signals are sent to an oscilloscope, and a displacement–time history is obtained. The number of measurements is limited to the number of coils present in the sensor. Nurick [9] has also developed a discrete measurement technique consisting of an array of photo voltaic diodes used to measure the deflection–time history of blast-loaded structures. The resolution of the measurement is dependent upon the number and spacing of the diode sensors.

The main drawback with discrete measurement systems is that they only provide instantaneous velocity measurements at a limited number of points along the projectile's path rather than an essentially continuous set of measurements. Some measurement systems, specifically high-speed photography, are also very expensive.

A more desirable velocity measurement system is one which measures the projectile motion continuously during an impact event. One method capable of continuous measurement is based on the concept of laser interferometry and has been used by Hodgkinson et al. [10], Gupta and Chiang [11] and Wu et al. [12]. The principle of laser interferometry is to intersect two coherent laser beams to form a small, ellipsoidal measuring volume. When the beams intersect, they form fringes. As the projectile passes through these fringes, light of different intensities is scattered. The frequency of the light-intensity change can then be detected using a photodetector. The data are represented as a velocity–time history for the impact event.

Espinosa et al. [13] used laser interferometry to simultaneously measure the projectile velocity and the back-face motion of the target. A normal velocity interferometer was used to measure the projectile velocity and a multi-point normal displacement interferometer was used to measure the target motion. It was necessary with this technique, however, to improve the reflectivity of the back surface of the targets by gluing a thin mylar sheet onto them and then depositing a thin film of aluminium vapour.

While laser interferometers do provide the desired continuous measurements for the impact event, they have some drawbacks. Current laser interferometer systems are quite expensive to purchase and the data reduction can often be quite time consuming and complex. As observed by Espinosa et al., it may also be necessary to alter the target to enable measurement.

Another method capable of continuous measurement during an impact event is through the use of a projectile with onboard instrumentation. An example of this method [2] consists of a projectile instrumented with either a load cell or accelerometer. The load cell/accelerometer is attached to an oscilloscope with thin, light wire leads that uncoil as the projectile travels down the gas gun barrel. The system is capable of measuring the time history of force or acceleration during impact. When using this method, the vibrations corresponding to the natural frequency of the projectile system has to be removed. The major drawback with this system is that the velocity is limited to approximately 50 m/s. Above this value the wire leads tend to break more frequently, resulting in a loss of signal. In addition, the mass of an instrumented projectile is much greater than that of a standard round.

A more recent continuous measurement technique, which is cost-effective and simple to operate, is the laser line velocity sensor (LLVS). Ramesh and Kelkar [14] originally developed the LLVS at Johns Hopkins University for use in flyer plate impact experiments. In this experiment, a plate is propelled down the barrel of a gas gun and impacts the target. The flyer plates are usually travelling at velocities on the order of 100 m/s. The initial velocity of the flyer plate is a critical measurement used in the evaluation of the effect of high shear or shock loading on material response. Ramesh and Kelkar have used the LLVS system to measure the displacement of flyer plates prior to impact, and hence determine the initial plate velocity and acceleration.

This paper presents the development and enhancement of the LLVS system for use in ballistic impact experiments. In this type of experiment, the enhanced LLVS system, hereafter referred to as the enhanced laser velocity system (ELVS) is used to continuously measure the motion of free-flying projectiles prior to and during the impact event. Whereas the original LLVS was simply used to obtain the initial impact velocity, the ELVS has been further developed to provide time histories of displacement, velocity, force, and energy and naturally the cross-plotting of such results.

Although the results presented in this paper deal with the application of the ELVS to hard and soft armour composite materials, the technique is equally applicable to a wider range of engineering materials, including metals and wood. However, it is not recommended to use the system for brittle materials, such as concrete where obvious problems will arise due to spalling, flying debris, and the like.

3. Enhanced laser velocity system (ELVS)

The ELVS, shown in Fig. 1(a), allows for continuous measurement of the projectile displacement before and during a ballistic impact event. The basis of this method is quite simple. A sheet of laser light is emitted from a diode laser (#1) and diverges in both the horizontal and vertical planes. The diode laser contains specialized line generating optics which produce a sheet of light with relatively uniform intensity along the width, except at the edges. The diverging sheet then passes through two plano-cylindrical lenses. The first of these (#2) collimates the sheet in the horizontal plane, while the second (#5) collimates the sheet in the vertical plane. An aperture (#3) and neutral density filter (#4) are placed between the two cylindrical lenses to block out the edges of the sheet which are of significantly non-uniform intensity, and to reduce the overall intensity of the laser sheet, respectively. The result is a sheet of laser light with uniform width, thickness and intensity. In our system, the width of the laser sheet is 25.4 mm (1.0″) and the thickness is 1.0 mm (0.04″). The sheet is then focused by a symmetric-convex collector lens (#6) onto the active area of a silicon PIN photo-detector (#7) which reads the intensity of the laser sheet. The sheet intensity is then recorded as a voltage by an oscilloscope. All components of the ELVS are mounted on an optical rail to allow for optimum alignment.

The diode laser that has been used has a wavelength of 670 nm, produces 1 mW of power, and is classified as a Class II, eye safe laser by The United States Center for Devices & Radiological Health (CDRH). The silicon PIN photo-detector has a rise/fall time of $\leqslant 7$ ns and remains significantly sensitive up to a bandwidth of 50 MHz. More specific details of the ELVS components can be found in [15].

3.1. Principle of operation of the ELVS

The basic principle of the method is shown in Fig. 1(b), with the corresponding voltage–time curve, from an actual impact test, given in Fig. 2. The target impacted in this test was an 18.5 mm

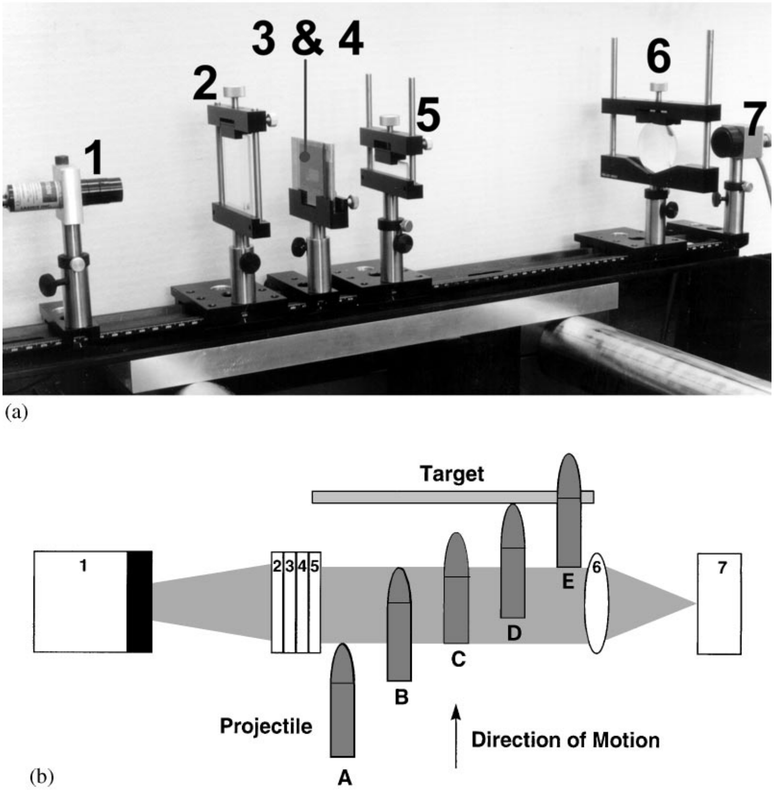

Fig. 1. The ELVS (where 1 is the line laser, 2 is the first cylindrical lens, 3 is the aperture, 4 is the neutral density filter, 5 is the second cylindrical lens, 6 is the collector lens, and 7 is the photo-detector). (a) photograph of the system and (b) schematic showing the principle of operation of the system.

thick, glass–fibre reinforced composite laminate. While the projectile is outside the sheet (up to position A in Fig. 2), the oscilloscope shows the maximum voltage that can be obtained. This is referred to as the *maximum light intensity*. As the projectile moves from position A to B, it blocks out the sheet and the intensity drops in proportion to the amount of light blocked. The minimum voltage that can be obtained when the sheet is completely blocked is referred to as the *minimum light intensity*. This value is approximately 0.04 V because the photo-detector registers background light. Since the projectile ($\sim$ 46 mm long) is longer that the sheet (25.4 mm) in this case, it continues to block out the sheet until the back end of the projectile reaches the front of the sheet, i.e., from B to C in Fig. 1(b). This results in a “null” period (B to C in Fig. 2), where the intensity of the sheet stays constant at the minimum value. From position C to E the projectile leaves the sheet causing the intensity to rise with a corresponding rise in voltage. Position D is the point at which impact occurs. This is measured from the known stand-off distance between the sheet and the target and is then verified by the reduction in projectile velocity at this point. Beginning at this point and until the end of the voltage–time curve, the data recorded provide a continuous measurement of the impact event.

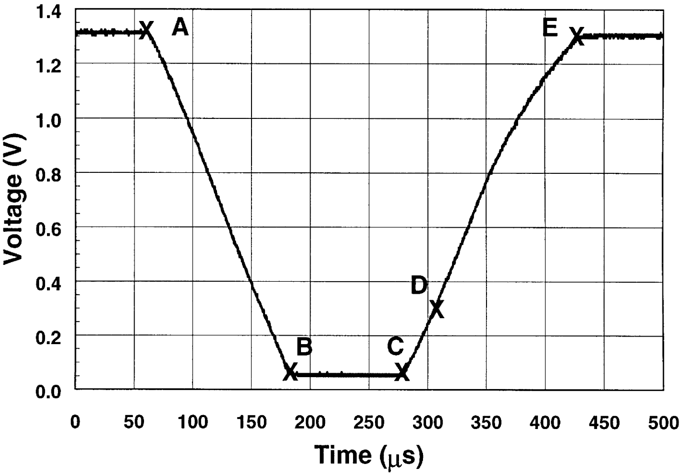

Fig. 2. Sample voltage–time curve from a ballistic impact test on a glass fibre-reinforced composite laminate.

In order to convert the voltage measurements into useable displacement data, the relationship between voltage and displacement must be obtained by performing a calibration test. Once this is obtained, the velocity can be determined, leading to the calculation of the acceleration, force and energy values.

4. Calibration

The calibration data were obtained by performing a number of "no-target" ballistic tests. The projectiles used for these calibration tests were 2.8 g blunt aluminium cylinders, 46 mm in length. The ELVS was used to measure the motion of the projectile. A voltage–time curve for one of the "no-target" calibration tests is shown in Fig. 3. The data obtained from the calibration test are normalized for displacement by multiplying each time step on the x-axis by the striking velocity of the projectile, v_s. This value is found by dividing the projectile length by t_{AC} (the time between points A and C in Fig. 3). In this manner, a voltage–displacement data set with the same number of data points as a ballistic impact test is obtained. This calibration data, in the form of a look-up table, is then used with data from a ballistic impact test to determine the projectile displacement–time history. If a test value falls between two calibration points the appropriate value is found through linear interpolation between existing points. This method ensures that the test displacement–time results always reflect the original calibration data. Laser intensity is normalised to account for ambient light conditions, thereby eliminating ambient light variations.

A problem sometimes encountered when performing impact experiments with our system is that the maximum laser intensity, and hence the maximum voltage, is not always the same for each test. The Lexan sheets protecting the lenses may get dirty or scratched or the laser itself may get dirty, and thus the intensity of the sheet diminishes resulting in a drop in the maximum voltage. It is therefore useful to normalize the calibration so that if the maximum voltage changes, the calibration is adjusted accordingly.

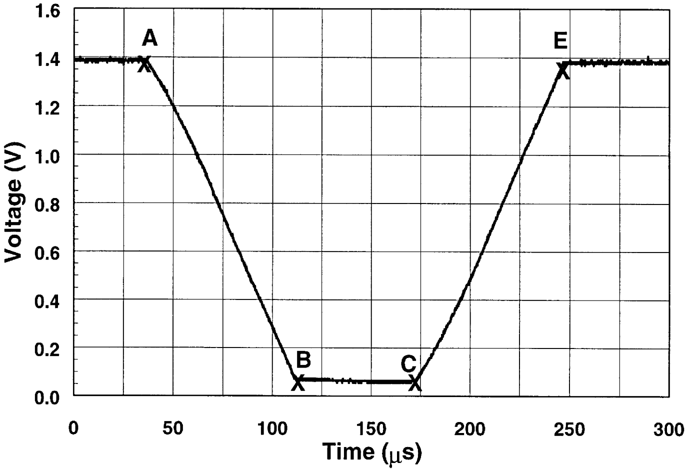

Fig. 3. Voltage–time curve for a 'no-target' test.

5. Data analysis

The process of data reduction from the initial input of raw test results to the final output of results is straightforward. The raw data points acquired from the digital oscilloscope are first read into the analysis program and then converted into voltages. The voltage–time curve is converted into displacement–time values using the calibration look-up table described in the previous section. The displacement–time curve is then differentiated to determine velocity values. The acceleration values are calculated by a second differentiation, and from these, force values are determined. Energy absorption values are obtained by taking the difference between the incident projectile energy ($\frac{1}{2}\, m_{\mathrm{proj}} v_{\mathrm{s}}^2$) and the projectile energy at any time during the impact event ($\frac{1}{2}\, m_{\mathrm{proj}} v^2$), where m_{proj} is the projectile mass, v_{s} is the projectile striking velocity, and v is the instantaneous projectile velocity.

To ensure that the ELVS functions properly during the test and to ensure that the data obtained from the test is valid, a consistency check can be performed on the voltage–time data. This check consists of a calculation of the projectile length. For a projectile that is shorter than or equal to the width of the laser sheet, w_{ls}, the projectile length, l_{proj}, is calculated from

$$l_{\mathrm{proj}} = \frac{w_{\mathrm{ls}}}{V_{\mathrm{full}} - V_{\mathrm{blocked}}}\,(V_{\mathrm{A}} - V_{\mathrm{B}}), \quad \text{for } l_{\mathrm{proj}} \leqslant w_{\mathrm{ls}}\,, \tag{1}$$

where V_{full} is the maximum voltage that can be obtained, V_{blocked} is the minimum voltage that can be obtained when the sheet is completely blocked, and V_{A} and V_{B} are the voltages at points A and B in Fig. 2, respectively. It should be noted that V_{A} will always be equal to V_{full}, however, V_{B} will be greater than V_{blocked} when l_{proj} is less than w_{ls}. For a projectile that is longer than w_{ls}, the projectile length is calculated from

$$l_{\mathrm{proj}} = \frac{w_{\mathrm{ls}}}{V_{\mathrm{full}} - V_{\mathrm{blocked}}}\,(V_{\mathrm{A}} - V_{\mathrm{B}}) + \frac{w_{\mathrm{ls}}}{t_{\mathrm{AB}}}\, t_{\mathrm{BC}}, \quad \text{for } l_{\mathrm{proj}} > w_{\mathrm{ls}}\,, \tag{2}$$

Table 1
Projectile length data check for the ELVS

Test	Calculated length (mm)	Actual length (mm)
Target (Fig. 2)	46.3	46.1
No-target (Fig. 3)	45.7	46.0

where t_{AB} is the time duration between points A and B in Fig. 2, and t_{BC} is the time duration between points B and C in Fig. 2. The calculated value for the projectile length is then compared to the actual projectile length measured prior to testing. As an example, the data checks performed on the curves in Figs. 2 and 3 are shown in Table 1.

6. System capabilities and limitations

6.1. Displacement resolution, maximum velocity, and signal noise

The silicon PIN photo-detector has a rise/fall time of $\leqslant 7$ ns and remains significantly sensitive up to a bandwidth of 50 MHz. Use of a 150 MHz oscilloscope ensures that the acquisition rate is well above the Nyquist frequency [16]. The vertical resolution of the oscilloscope is 8 bits or 256 vertical divisions. Ideally the maximum displacement resolution can be as high as 25.4 mm/256 digits, which is about 10 divisions/mm (or 0.1 mm of displacement). In reality, the full scale of the oscilloscope is difficult to utilize and the working resolution, prior to data reduction, is 6.25 div/mm (or 0.16 mm of displacement). The inherent system noise is just slightly below ± 0.08 mm. Combining the minimum rise/fall time of the detector with the resolution limitations of the oscilloscope results in a maximum velocity of 0.16 mm/7 ns or $\sim 23{,}000$ m/s. In practice, the fastest projectile velocity measured thus far has been approximately 15 times less than this. Due to safety concerns with the current powder gun set-up, not the ELVS limitations, a striking velocity of 1500 m/s is our operating limit for current testing.

Numerical differentiation is performed over a user-defined range of data points. This reduces the amplification of noise through successive differentiation and introduces a measure of smoothing. The number of data points is selected such that the resultant displacement range is 1 mm. No other signal filtration is used. Future developments will include the use of FFT techniques to filter out high-frequency noise components.

6.2. Repeatability

To illustrate repeatability, approximately 100 “no-target” tests with varying velocities were performed. The voltage–time curves from five representative tests are shown in Fig. 4. The velocities ranged from 204 to 460 m/s. All tests were performed using blunt-tipped projectiles, 46 mm in length. When using the ELVS in its simplest form, the instant of time and position of the projectile as it enters and exits the laser sheet can be obtained. From this, the velocity can be

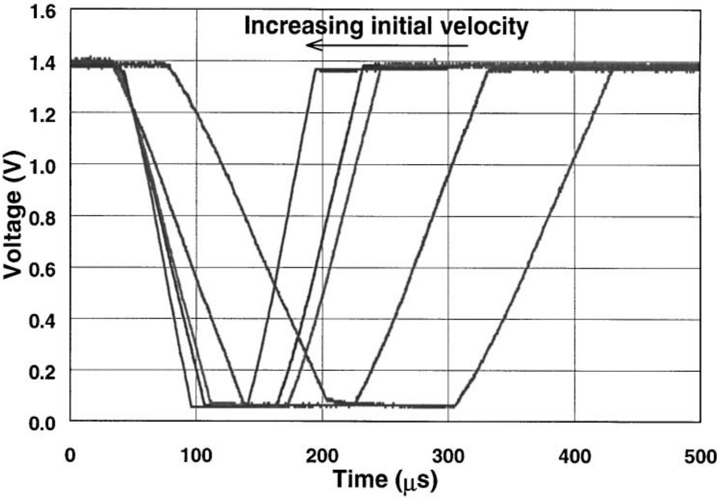

Fig. 4. Voltage–time curves for 'no target' tests at different velocities.

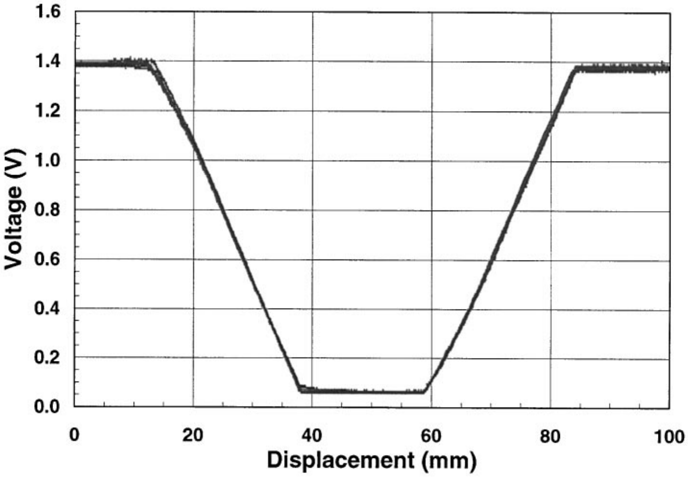

Fig. 5. Voltage–displacement curves showing repeatability of the ELVS.

calculated. By multiplying the time axes on all curves by the projectile striking velocity, v_s, the voltage–displacement curves shown in Fig. 5 can be generated. All these curves superpose within 5% of the expected velocity value, and clearly show the repeatability of the ELVS.

6.3. Limitations

The primary limitation of the technique is that it is essentially a side view of the impact event. If the projectile is short and the target deforms sufficiently, then the projectile will leave the field of view too early and/or will be masked by the target. Even with extra-long projectiles, textile targets pose problems in that they deform excessively. High-speed photography has been successfully used in conjunction with the ELVS when a camera light source, with a wavelength outside the primary sensitivity of the detector, is used. Projectile attitude of up to 5° should not alter results noticeably, however, high-speed photographs have indicated that no such magnitudes of attitude are present in our tests. Within the measurement window of the ELVS, projectile angle deviation is not an issue with soft armour. For hard armour this deviation may occur near the end of the acquisition, if it occurs at all, and must be considered when analysing the data. Occasionally the last 3 or 4 mm of data must be disregarded. In cases where the projectiles rebound, the data analysis yields decreasing displacement and hence a negative projectile velocity as expected.

The data analysis presented here assumes that the target absorbs all of the available energy. If projectile deformation occurs, it also must be taken into account.

7. Test results

The ELVS has been successfully employed in a large number of impact tests performed at the impact facility at UBC [15,17]. The use of this system and the subsequent data reduction process are demonstrated for four of these impact test cases. The first two tests consist of a hardened steel projectile fired at a composite laminate (hard) target. The second set of tests consists of an aluminum projectile fired at a fabric (soft) target.

7.1. Composite laminate impact results

The targets used were S2-glass woven fibre-reinforced polymer composite plates with a thickness of 12.7 mm. The targets were simply supported around all four edges. The projectiles were hardened steel with a 37° conical tip angle, a mass of 13.2 g, and a length of 46 mm. In test #C1, the impact velocity was 313 m/s and the projectile completely perforated the target. In test #C2, the impact velocity was 168 m/s and the projectile came to a complete stop in the target.

The displacement–time and velocity–time curves for both impact tests are shown in Figs. 6 and 7, respectively. In all these curves, the data are plotted such that impact occurs at the origin of the curve. For test #C1, the projectile slowed down only slightly before perforating the target, and the duration of the impact event was approximately 90 μs. For test #C2, the projectile was completely arrested by the target, at about 240 μs. Oscillations near the end of the velocity–time curve for test #C1 (where the projectile perforated the target) occur during constant velocity portions of projectile flight. This may be attributed to projectile tumbling after perforation.

Fig. 8 shows the force–displacement results for both impact tests. Results are also shown for a static test with the same boundary conditions (static deflection) and a static test where the projectile was used as an indenter on the composite target, supported on a rigid steel base (static indentation). Observation of this figure shows that early in a ballistic test, the composite target does not have time to bend, and the ballistic results closely match the static indentation results. As the composite target deforms globally, the ballistic results approach the static deflection results. The good agreement between the static and ballistic results show that this material exhibits relatively

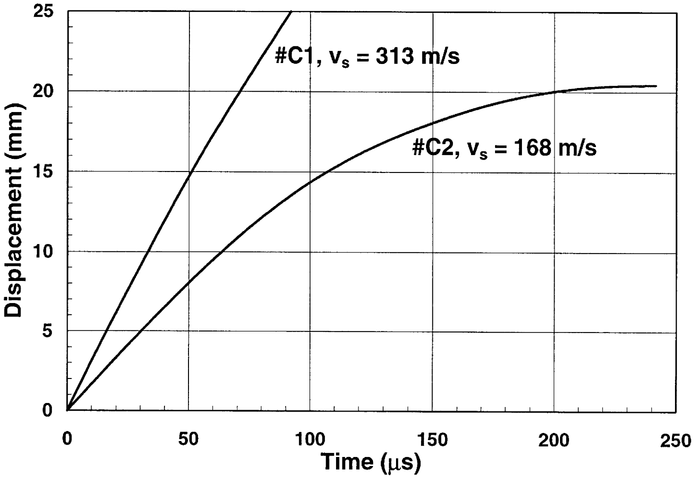

Fig. 6. Projectile displacement–time results for composite laminate impact tests.

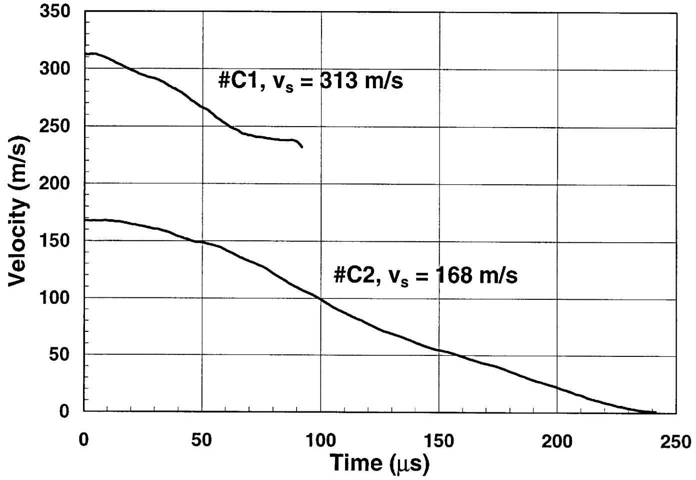

Fig. 7. Projectile velocity–time results for composite laminate impact tests.

strain-rate insensitive behaviour within the 52 tests conducted, at least in this range of loading rate. This conclusion is consistent with the findings of Thiruppukuzhi and Sun [18].

The absorbed energy–displacement curves are shown in Fig. 9. For test #C1, where the projectile perforated the target, the absorbed energy is 288 J. The incident projectile energy for this test was 647 J. For test #C2, where the projectile was stopped, the total absorbed energy is 186 J, which is identical to the incident projectile energy. The results from a static deflection test are also shown for comparison. Again, there is good agreement between the ballistic and the static deflection results.

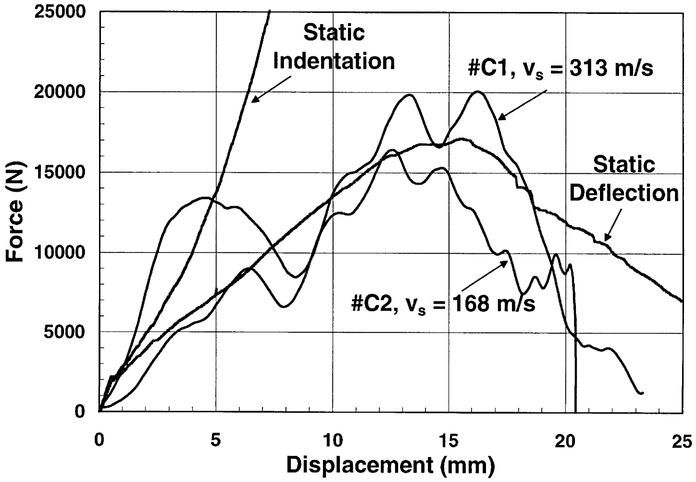

Fig. 8. Force–displacement results for composite laminate impact tests, including a static indentation test and a static deflection test for comparison.

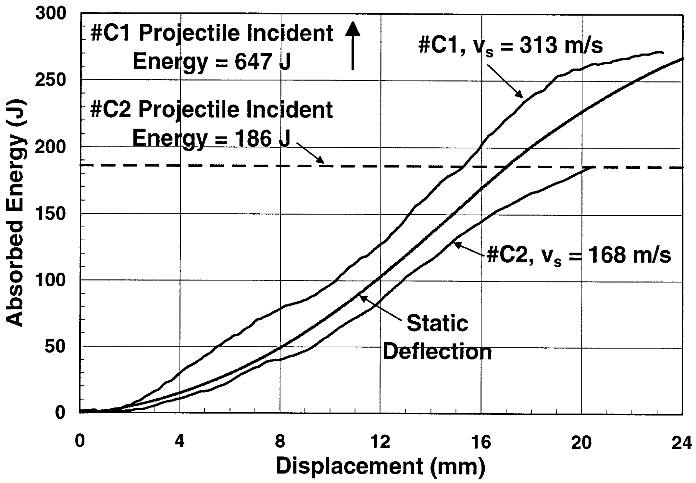

Fig. 9. Absorbed energy–displacement results for composite laminate impact tests, including a static deflection test for comparison.

7.2. Fabric impact results

The targets were composed of eight layers of Kevlar® 129 fabric, and were clamped at the top and bottom edges. The projectiles used were 2.8 g, blunt-tipped aluminium cylinders, with a length of 46 mm. In test #F1, the impact velocity was 428 m/s, and the projectile completely penetrated all eight layers of the target (i.e., the target was perforated). In test #F2, the impact velocity was 267 m/s and the projectile did not penetrate any of the layers in the target.

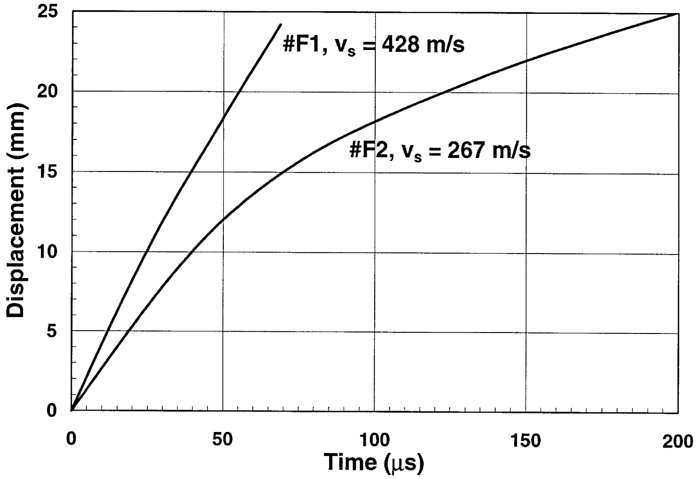

Fig. 10. Projectile displacement–time results for fabric impact tests.

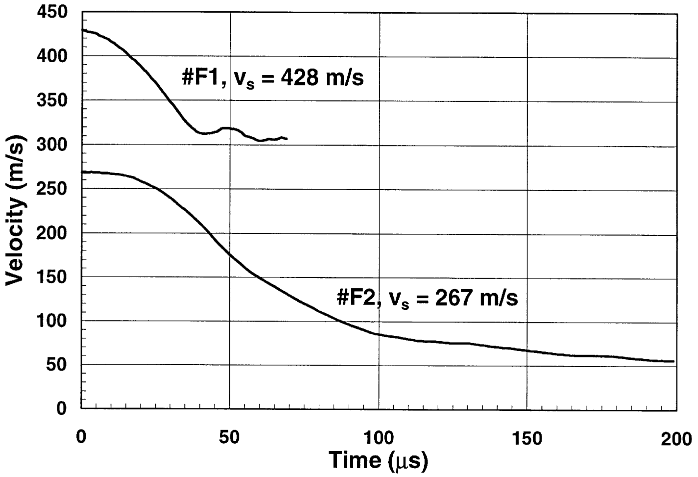

Fig. 11. Projectile velocity–time results for fabric impact tests.

The displacement–time curves for both tests are shown in Fig. 10, and the projectile velocity–time curves are shown in Fig. 11. In all these curves, the data is plotted such that point C (Fig. 2) corresponds to the origin of the curve. When fabrics are subjected to impact, they tend to deform more significantly than composite laminate targets. Therefore, some information during the latter stages of the impact event is not captured by the measurement system. For test #F1, the projectile decelerated to a velocity of 307 m/s before perforating the target. For test #F2, the projectile decelerated to a velocity of 57 m/s within the measurable range. As with the composite laminate impact results, oscillations near the end of the velocity–time curve for test #F1 (where the projectile perforated the target) occur during constant velocity portions of projectile

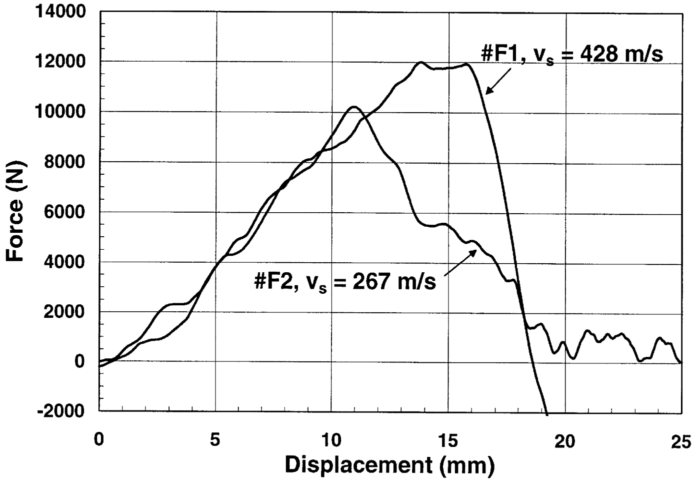

Fig. 12. Force–displacement results for fabric impact tests.

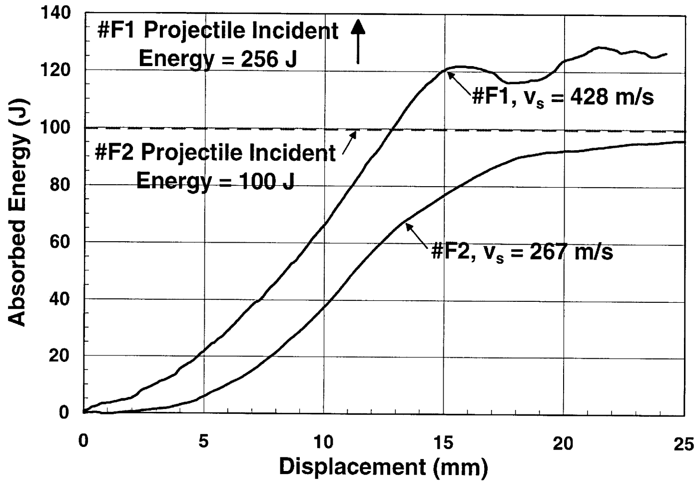

Fig. 13. Absorbed energy–displacement results for fabric impact tests.

flight. As stated in the previous section, this may be attributed to projectile tumbling after perforation.

The force–displacement results of both fabric tests are shown in Fig. 12. In test # F1, the force on the projectile increases to a value of approximately 12 kN, and remains relatively constant for 2 mm of projectile displacement. This plateau region might represent the constant frictional force between the projectile and the target during penetration. In test # F2, the force reaches a maximum value of approximately 10 kN, and then decreases. Post-test observation showed that the target experienced a permanent 'bulge' deformation on the order of 10 mm in depth. Hence, the peculiar behaviour of the force–projectile displacement curve after the peak force is reached could represent the loss of elasticity or tautness of the fabric due to either the formation of the bulge or due to other effects within the material itself. The absorbed energy–displacement curves are shown in Fig. 13. For test #F1, where the projectile perforated the target, the absorbed energy at the maximum measured displacement is 127 J. The incident projectile energy for this test was 256 J. For test #F2, where the projectile was stopped, the absorbed energy at the maximum measured displacement is 96 J. This is slightly lower than the incident projectile energy of 100 J due to the limitations on the measurable amount of target deformation.

8. Summary and conclusions

The ability to continuously measure the projectile motion during a ballistic impact event is very much desired. Continuous measurements enable one to obtain a history of the impact event, and allow a closer examination of the energy absorbing mechanisms that occur in a target during impact. Most current measurement systems usually allow for only discrete measurements, primarily the impact and residual velocities. A small number of continuous measurement systems exist and are used in ballistic impact experiments. These, however, tend to be expensive, and often involve quite complex data analysis.

The enhanced laser velocity system (ELVS) presented here continuously measures the projectile displacement during ballistic impact events. The system is easy to operate, cost-effective and provides accurate and detailed information about the impact event. The data analysis is fairly straightforward, making use of simple mathematical operations to obtain projectile velocity, acceleration, force and energy histories during the impact event. The extensive amount of information that the system provides is invaluable for detailed understanding of the behaviour of a wide variety of materials and structures subjected to ballistic impact. Furthermore, the continuous measurement of data can be of potential benefit to development and verification of analytical/numerical models for simulation of ballistic events.

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