EVALUATION OF IMPACT FORCE MEASUREMENT SYSTEMS FOR ASSESSING BEHIND ARMOUR BLUNT TRAUMA FOR UNDEFEATED BALLISTIC HELMETS

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Summary

With the emergence of new technologies for ballistic protection, there now exists the possibility of having novel helmet designs with improved performance against high energy bullets. While the new helmets are capable of defeating these threats, significant behind armour deformation may still produce sufficient loading to the head to cause serious injury. Previous work at the University of Virginia for the U.S. Army Natick Soldier Center and at the Defence R&D Canada-Valcartier established a correlation between head injury and measured force on the skull as a result of non-penetrating projectile impacts to a helmet. Current efforts comprise the development of a test methodology based on these findings to be potentially included in a revised version of the NIJ 0106.01 standard and future Canadian ballistic helmet specifications. An evaluation of potential behind armour impact force measurement systems to be installed in a modified Hybrid III headform is presented. Performances of polyvinylidine fluoride (PVDF) gauges and miniature piezo-electric load cells were compared. Instrumentation and methods were evaluated for accuracy and repeatability in the context of performance standard testing. Experimental results and recommendations for future work are presented.

1. Introduction

Ballistic helmets were introduced several years ago to protect military and law enforcement personnel against penetrating injuries caused by impact with shrapnels from fragmenting munitions and, since more recently, small caliber ammunition (handgun and rifle bullets). Such impact usually results in critical (AIS=5) to unsurvivable (AIS=6) injuries as categorized by the Abbreviated Injury Scale (AIS) system [AAAM 1985]. The benefits of ballistic helmets in stopping high-velocity projectiles are incontestable. However, even if the projectile is stopped, the helmet shell indentation formed during impact may apply sufficient force to cause head injury from blunt impact. This is an important and immediate concern especially since the introduction of novel lightweight composite materials for ballistic protection that are lighter and thus more compliant under impact.

Methods to assess penetration performance of ballistic helmets are relatively straightforward. They are defined in several test standards [NIJ 1981; MIL-H-44099A 1986; H.P White Laboratory 1995; NATO 1996; MIL-STD-662F 1997] and the results obtained are recognized for ranking helmet performance. For non-penetrating ballistic impact, there is currently no widely accepted test method to evaluate the performance of helmets. However, recent work at DRDC Valcartier [Bolduc 1998; Bolduc and Tylko 1998] and at the University of Virginia for the U.S Army Natick Soldier Center [Bass, Boggess et al. 2000; Bass, Boggess et al. 2003] led to two major outcomes: a) a validated procedure for measuring the load to the head applied by the backface deformation of helmet and, b) an human injury tolerance threshold. In this research program, the physical response of a helmeted surrogate head (modified Hybrid III headform) was characterized for a series of ballistic impacts.

Experimental setup and test conditions were reproduced with post mortem human subjects (PMHS) to identify the most suitable biomechanical parameter for predicting the risk of injury. The results showed that the dynamic peak force measured at the surface of the skull correlates well with the occurrence of skull fracture [Waclawik, Bolduc et al. 2002]. The outcomes of this work were used to develop a transfer function to transpose the injury risk curve from the PMHS to the head surrogate.

The dynamic force on surrogate head and PMHS skulls was measured with PVDF (polyvinylidine fluoride) film sensors. They have good dynamic sensing characteristics and do not affect the mechanical properties of the structures (e.g. bone) on which they are mounted. These transducers were identified as the best option to characterize the localized load applied by the backface deformation of helmet at the surface of the human skull.

The objective of the study described in this report consisted in exploring other alternatives for measuring helmet backface loading. Current concerns with PVDF film sensors are the calibration, ease of use, and degradation of the gauges for potential use in helmet performance evaluation in the context of standard testing. To address this issue, a series of tests was conducted at Biokinetics ballistic laboratory with different transducers. Helmet backface loading conditions were reproduced with a pneumatic cannon and an instrumented impactor. The experimental results provide important information for the development of a standard test procedure for the performance evaluation of ballistic helmets.

2. Materials and Methods

2.1 Impactor Design

Preliminary work showed that backface deformation of ballistic helmet may introduce substantial variability in the load applied to an instrumented headform [Anctil and Shewchenko 2003]. To provide a more repeatable input to the measurement systems being evaluated, ballistic helmets were not used in this study. Instead, the backface loading conditions were estimated and reproduced with an instrumented impactor launched from an air cannon.

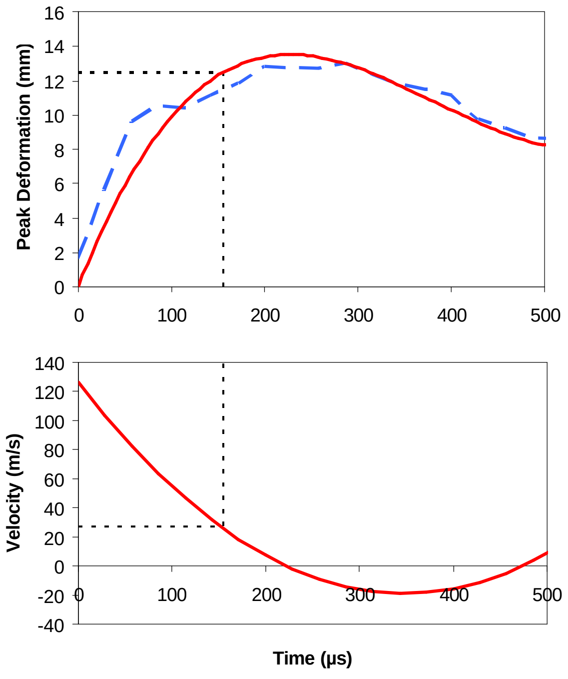

Figure 1: Backface deformation (above) and velocity (below) profiles. The dotted line represents the raw data.

The impactor striking velocity was estimated from the backface deformation of a composite plate impacted with a 9 mm FMJ bullet 124 grains at 350 m/s. The composite plate was made of a woven aramid laminate used typically for ballistic helmet. The deformation profile was obtained form high speed video (provided by the Délégation Générale pour l'Armement) and derived to obtain the velocity as a function of time. Figure 1 shows that for a plate deformation of 12.5 mm (the typical helmet standoff value) the residual velocity was approximately 30 m/s.

The mass of the impactor was assessed using the momentum conservation principle which states that the momentum (the mass of an object multiplied by its velocity) is the same before and after the impact. Thus, if $m_1v_1=m_2v_2$, then m_2= (8.0 g x 350 m/s) / 30 m/s = 93 g.

The convex impact surface shape of the impactor was determined from the permanent deformation of ballistic helmets after defeating 9 mm FMJ bullets. The impactor diameter was set to 37 mm to match the internal diameter of the air cannon barrel. The impactor assembly is shown in Figure 2. An accelerometer (PCB Model 350A03) was installed on the rear end of the impactor's aluminium head. The foam body provided protection to the accelerometer and strain-relief for the wire. It also stabilizes the impactor during flight.

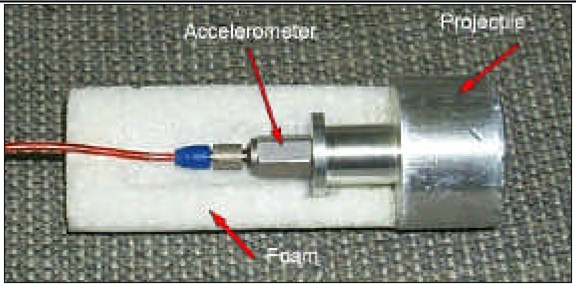

Figure 2: Instrumented impactor.

2.2 Force Transducers

Two different PVDF force sensors and a miniature load cell were selected for this experimental evaluation.

The first PVDF force transducer model selected was the PVF11-.25-EK manufactured by Dynasen Inc., Goleta, CA. It was similar to the unit used during the development of the helmet backface force measurement technique mentioned above. This gauge is a superimposed piezoelectric/strain gauge arrangement combining one biaxially-stretched stress gauge to a bi-directional strain gauge (Figure 3). Since PVDF force sensors are sensitive to bending, concurrent strain measurement allow to correct the output signal of the PVDF gauge to keep only the normal force component. While essential for measurements on the PMHS skulls, the strain gauges were not used in this work because theses sensors were mounted on a rigid surface where no bending occurred. This sensor can measure force greater than 1000 N and it has as an active sensing area of 40 mm^2.

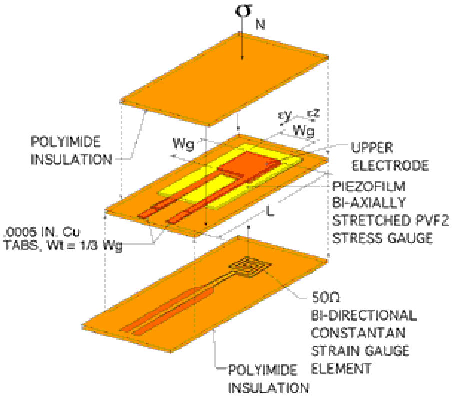

Figure 3: Superimposed PVDF force/strain gauge (Dynasen Inc.).

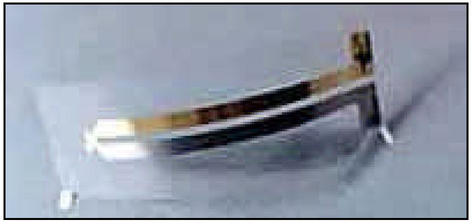

Figure 4: PVDF M25-25-PL (Ktech Corp.).

The second PVDF sensor model was a Piezotech PVDF M25-25-PL (Ktech Corp., Albuquerque, NM) and can measure transient pressures from 1 KPa to 40 GPa with an active sensing area of 25 mm^2 (Figure 4). It is thin (less than 25 µm) and adaptable to complex contours. This gauge is manufactured from 26-µm thick biaxially-stretched film and poled using the Bauer method.

A miniature piezoelectric load cell model No (SlimLine Sensor Model 9131B, Kistler Instrument Corp., Amherst, NY) was proposed as an alternative to the PVDF film sensors. This quartz dynamic transducer was selected because of its small size and its suitability to dynamic impacts. It has the ability to measure load up to 2500 N with a sensing area of 18 mm^2.

Figure 5: SlimLine Sensor Model 9131B (Kistler Instrument Corp.)

2.3 Experimental Setup

A schematic of the test setup is depicted in Figure 6. The force transducers were mounted on a rigid steel plate oriented normal to the line of fire. They were covered with a 10 mm thick RTV664 silicone pad to simulate the skin of the Hybrid III mannequin. The Hybrid III headform skin as a thickness of approximaltely 10 mm and a hardness of approximately 50-55 Shore A while the hardness of the RTV664 silicone pad corresponded to 54 Shore A.

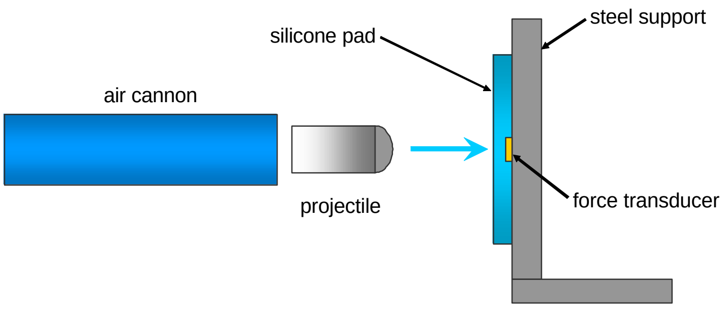

Figure 6: Test Setup.

A thin Teflon® sheet (0.025 mm thick) was placed under the PVDF sensors to provide electrical insulation from the steel support. A second Teflon® sheet was placed freely over the transducers to avoid any shear load transfer from the silicone pad during impact. The load cell was mounted such that the sensing surface protruded slightly over the support plate.

The signals of the force transducers were conditioned with charge amplifiers B&K, Model 2651 set to the appropriate gains to maximize signal to noise ratio. Anti-alias filtering was performed (Frequency Devices Inc., Model D64L4B, low-pass 4-pole Butterworth, cutoff frequency 40 kHz) on the signals prior to analog-to-digital conversion and data recording was conducted with a National Instruments' data acquisition board, Model PCI-6110 installed into a personal computer (Intel Pentium II – 233 MHz). The sampling frequency corresponded to 200 kHz. A National Instruments' input box Model BNC-2110 and coaxial cables were used to provide the necessary connections.

The velocity of the impactor was measured with a fiber optic time gate connected to the data acquisition board described above. The time gate was located at the end of the muzzle to evaluate the velocity when the impactor leaves the barrel. The measurement error associated with the response time of the sensors and the sampling rate (100 kHz) corresponded to ±0.31 m/s at 20 m/s and ±1.22 m/s at 40 m/s.

Each transducer was tested multiple times under various impact velocities around the target speed of 30 m/s. The lowest speed was limited by the air cannon capability and corresponded to 9.5 m/s. The highest speed was restricted by the accelerometer shock limit of 10,000 g which corresponded to impact velocities above 25 m/s. Further trials were conducted above this limit but the accelerometer was replaced by a dummy accelerometer to keep the mass of the impactor equal. No acceleration was recorded for these trials. A minimum of twelve tests were conducted for each force transducer.

3. Results

Typical results for an impact velocity of approximately 20 m/s are shown in Figure 7, Figure 8, and Figure 9 for the two PVDF film sensors and the load cell, respectively. The dynamic force applied by the impactor was obtained by multiplying its mass with the acceleration signal. Peak force measured by the force transducers are expected to be lower than the peak force applied by the impactor because the sensing area is smaller than the loading area.

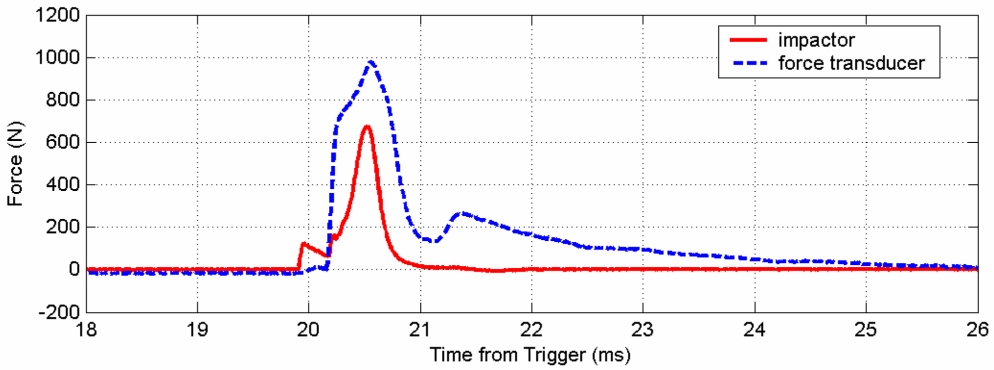

Figure 7: Typical response for Dynasen PVDF film sensor (v=20.1 m/s).

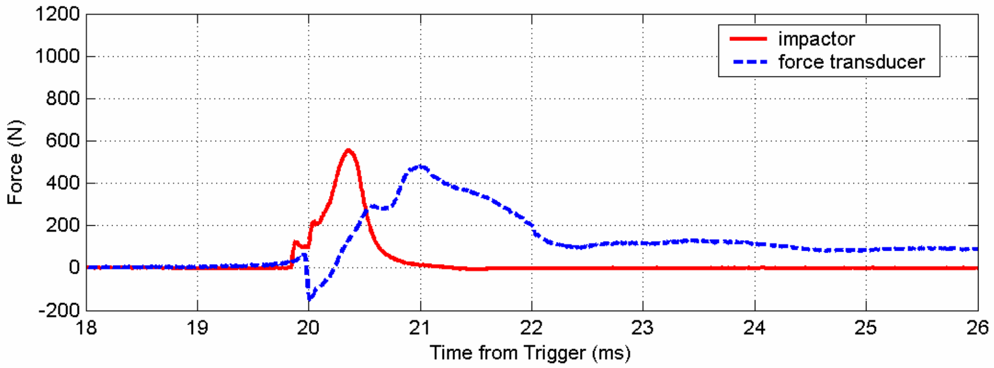

Figure 8: Typical response for Ktech PVDF film sensor (v=20.3 m/s).

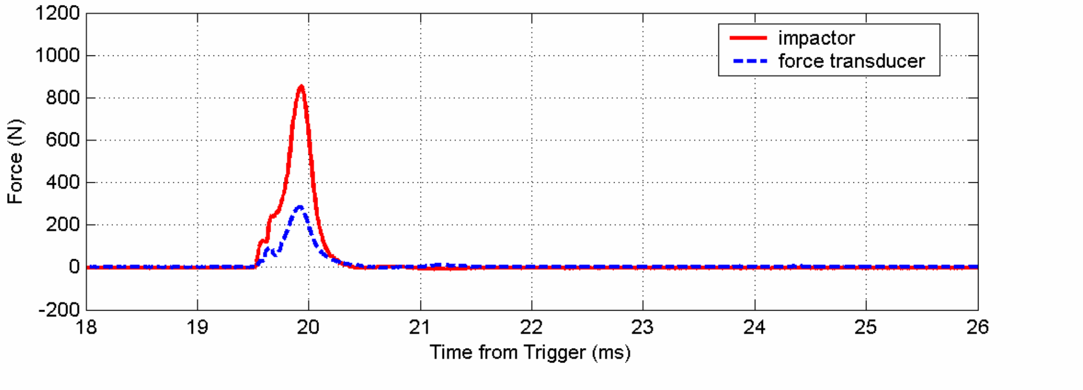

Figure 9: Typical response for Kistler load cell (v=20.2 m/s).

The response's shape, duration and time to peak recorded with the Dynasen PVDF film sensor shown in Figure 7 correlate relatively well with the accelerometer signal. The signal obtained for the other PVDF gauge (Ktech), however does not match the impactor trace (Figure 8). In fact, signal polarity changes are observed for the majority of the tests conducted with this sensor. It appears that these polarity changes are somehow related to inflection points on the accelerometer trace but the reason for this behaviour is unknown. Figure 9 shows that the shape, duration, and time to peak are very similar between the load cell response and the input force signal. A rather large difference exists between the peak forces.

Figure 10 shows the relationships between the peak force applied (impactor) and the peak pressure (force transducer) measured. Peak pressure values, calculated by dividing peak force by the sensing area, are used to compare the results obtained from one force transducer to another. Least squares fitting to the original data are illustrated with trend lines. Results obtained with the load cell are consistent over the entire range. A good correlation is observed for the Dynasen film sensor at lower input force but the correlation is rather poor at higher input force. The Ktech sensor has a large variability over the entire range of input force with no indication of a linear trend.

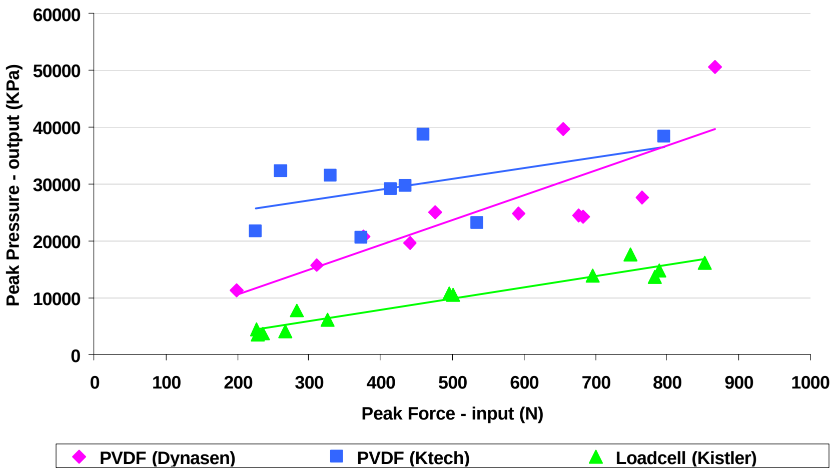

Figure 10: Output peak pressure vs. input peak force.

The quality of the least squares fitting is quantified with the correlation coefficient (r^2). The correlation coefficient is a number between 0 and 1, where a perfect fit gives a coefficient of 1. Correlation coefficient is computed using the following equations:

$$r^2 = \frac{SS_{xy}{}^2}{SS_{xx}\,SS_{yy}}$$

where:

$$SS_{xx} = \sum (x_i - \bar{x})^2$$

$$SS_{yy} = \sum (y_i - \bar{y})^2$$

$$SS_{xy} = \sum (x_i - \bar{x})(y_i - \bar{y})$$

Table 1 shows correlation coefficients values calculated for each of the three sensors. These results confirmed the observations described above. The best fit is obtained with the load cell. The Dynasen gauge shows good correlation while the linear fit with the Ktech sensor is poor.

Table 1: Correlation coefficients.

Force Transducer	r^2
PVDF (Dynasen)	0.67
PVDF (Ktech)	0.23
Load cell (Kistler)	0.93

3. Discussions

There are limited options for measuring dynamic force applied by the helmet backface deformation. PVDF film sensors and miniature load cell can be used in this application but each type of sensor has its own strengths and weaknesses. PVDF film sensors are compact (permitting superior gauge density), relatively inexpensive, and can be installed on curved surfaces. Current concerns are the ease of use, degradation, and calibration. Miniature load cells are robust and reliable but the space requirement is greater.

Peak pressure values obtained with the Dynasen gauges were comparable to those obtained at University of Virginia with the helmeted Hybrid III headform suggesting that the simplified impactor provided the appropriate dynamic loading. Also, even if the sample size was limited, this experiment shows that significant differences can be observed in the measured response recorded by the different transducers (Figure 10). For example, at a peak input force of 500 N, peak pressure values of approximately 10,500 kPa and 24,000 kPa were measured by the load cell and the Dynasen film sensor, respectively (note that the results obtained with the Ktech gauge are not considered here because of its poor performance). The difference observed should not pose a problem if the response of the sensor is linear over the expected loading range. However, transducers must be calibrated under the same conditions in order to compare their results.

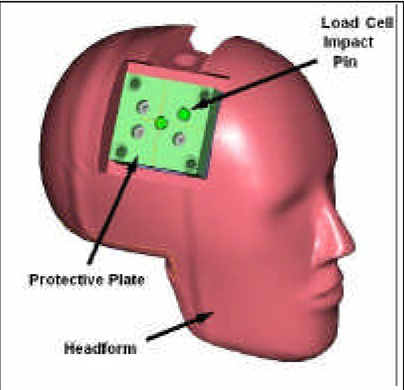

Figure 11: MLC headform.

Considering the advantages of the miniature load cell for helmet performance evaluation in the context of standard testing, additional work was conducted to integrate a series of these sensors into a surrogate head. The shape of the Hybrid III mannequin headform and the sensor pattern were similar to previous research studies [Bass, Boggess et al. 2000]. The preliminary concept is shown in Figure 11. Five load cells were mounted on a rigid module which can be installed on both sides of the headform. A piece of synthetic skin recovered the entire module. The headform assembly was mounted on a flexible Hybrid III neck. A sheet of pressure sensitive film was placed directly over the top surface of the load cell module to verify impact location.

Using the experimental setup described in Section 2, baseline testing was conducted with the first prototype of the headform instrumented with miniature load cells (MLC). Typical responses of the five load cells for an impact velocity of 20 m/s are presented in Figure 12. The impactor's accelerometer trace is indicated with a black dashed line using the secondary axis. Load cell positions and associated identification numbers are depicted in Figure 13 along with a digital scan of the pressure sensitive film used for this specific trial. Figure 12 shows that peak pressure value was significantly higher for load cell No. 3 suggesting that the load was concentrated over this transducer. The picture of the pressure sensitive film is in agreement with this affirmation. Negative values (tension) are believed to be caused by the torsion of the support plate during impact.

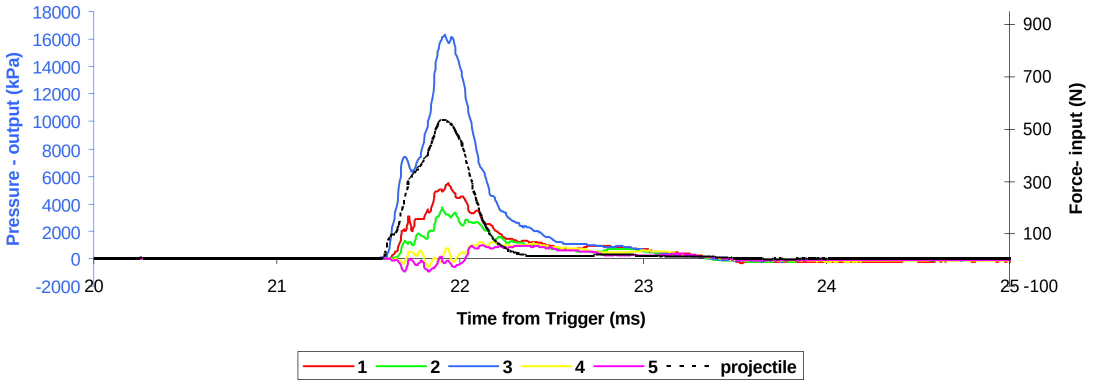

Figure 12: Typical response for load cell array (v=20.2 m/s).

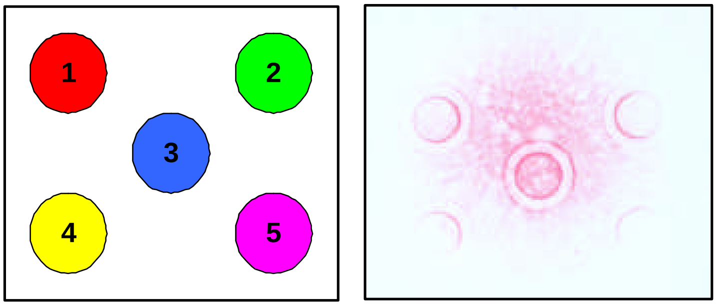

Figure 13: Load cell pattern and pressure sensitive film.

Overall test results are presented in Figure 14. For each trial, only the peak value of the five sensors was considered. The correlation coefficient was lower than the previous results for a single load cell. This is believed to be related to the fact that the impactor was not always centered over one of the transducers. Nevertheless, these results demonstrate the potential of the MLC headform to measure localized loads at the surface of the skull

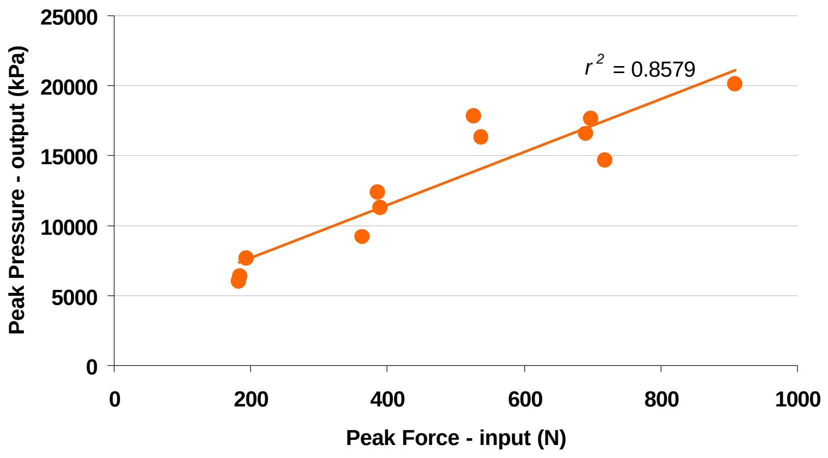

Figure 14: Output peak pressure vs. input peak force for the load sensing headform.

4. Conclusions

Three force transducers (two PVDF film sensors and one miniature load cell) were evaluated under loading conditions simulating helmet backface deformation. The correlation between the input force applied and the load measured was very good for the miniature load cell, good for one PVDF film sensor but poor for the second model. In addition, absolute force values measured by the transducers were significantly different from one sensor to another for the same input load. This stresses the need for calibration before use and verification of the gauges throughout testing. Further work was conducted to include load cell for standard testing of ballistic helmets considering the good performance and robustness of this type of transducer. A prototype instrumented headform with load cells was designed and built. Baseline testing was performed and the results demonstrated the potential for measuring localized dynamic loads at the surface of the skull.

Future work include the assessment of the headform response under ballistic impact and the development of a standard procedure for performance evaluation of ballistic helmets. It is planned also to add the capability of measuring pressure loads at the front and back of the MLC headfrom.

5. Acknowledgement

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