ASSESSMENT AND MEASUREMENT OF POTENTIAL BLUNT TRAUMA UNDER BALLISTIC HELMETS

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This paper investigates measurement techniques to evaluate ballistic impact protection in terms of head contact loads from non penetrating impacts on helmets. An aluminium head form instrumented with piezo-electric transducers, film sensors and accelerometers was used to measure impact forces applied by the back face deformation of helmets after ballistic impacts. The head form and an instrumented accelerated weight machine are also used to measure impact forces applied to the helmet and forces transmitted behind the helmet.

Radius of curvature of back face deformation data were also collected from ballistic impacts on helmets mounted on conditioned plastilina® and was shown to correlate with published studies from Wilber [4] and Byers [5] which established a correlation between the force required to fracture a human skull and radius of curvature of the striker. It is shown that backface deformation of potentially damaging levels can be generated behind typical ballistic helmets.

Keywords: Blunt trauma, Helmets, Ballistic protection

INTRODUCTION

The purpose of this study was to measure impact forces with different sensors in attempt to determine whether a relationship from the back face forces resulting from non penetrating impact and the forces required for injuries to the skull or brain can be found. The aim of the work was to evaluate these impact forces and use the information to further the development of a robust method of force measurement for helmet testing.

Bullet impacts transfer kinetic energy onto a small area and whilst a helmet may prevent penetration of the skull and brain from the ballistic impact, back face deformation (BFD) of the helmet could result in high contact loads to the skull causing shock waves and consequently serious head injuries. The relationships between behind helmet impact forces, energy and brain injury have not yet been defined.

PRELIMINARY TRIALS

Forensic analysis by Wilber[4] and reported by Byers[5] has established a relationship between the amount of force necessary to cause a skull fracture from the deformation found on the frontal bone. Wilber[4] related the size and shape of the permanent damage left by compressive fractures after fatal attack by blunt weapons such as hammers to the radius of curvature of the impacting weapon, figure 1.

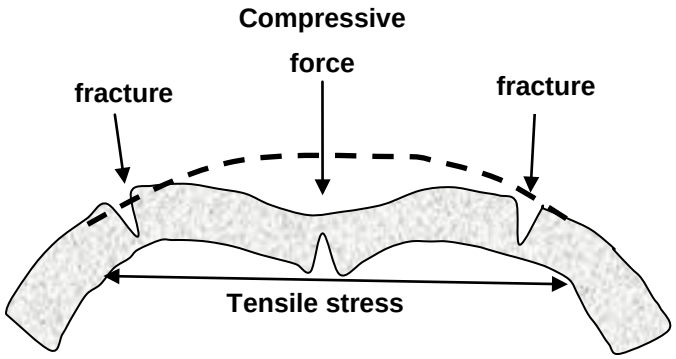

Figure 1. Skull fractures induced by impact force (after Byers [5])

A program of ballistic trials was carried out to investigate if the radius of curvature from back face deformation caused by blunt weapons described by Wilber[4] could also be extrapolated to ballistic impact on helmets. Preliminary ballistic trials with 9mm DM11A1B2 ammunition fired from a proof barrel at 5 metres were carried out. To ensure that the ballistic impacts caused measurable BFD in these initial trials aramid helmet shells without impact mitigating materials such as trauma padding or specialist carriage systems were used. The velocity range was 283 - 459 ms^{-1} all bullets were stopped and significant measurable back face deformations were seen.

Following the above trial, plastilina® pre-conditioned and calibrated as in a ballistic body armour test was chosen as a suitable witness material to back the helmet shells and measure the radius of curvature of the indents behind the helmets. Trials at the velocities that had produced measurable back face deformations with 9mm DM11A1B2, 30cal and 50cal fragments were carried out on the helmet shells. The indentations in the Plastilina® were measured and the radius of curvature estimated. These tests were repeated with a set of helmets with mitigating padding and fitted carriage systems and figure 2 shows the test results plotted and superimposed on the forensic data graph.

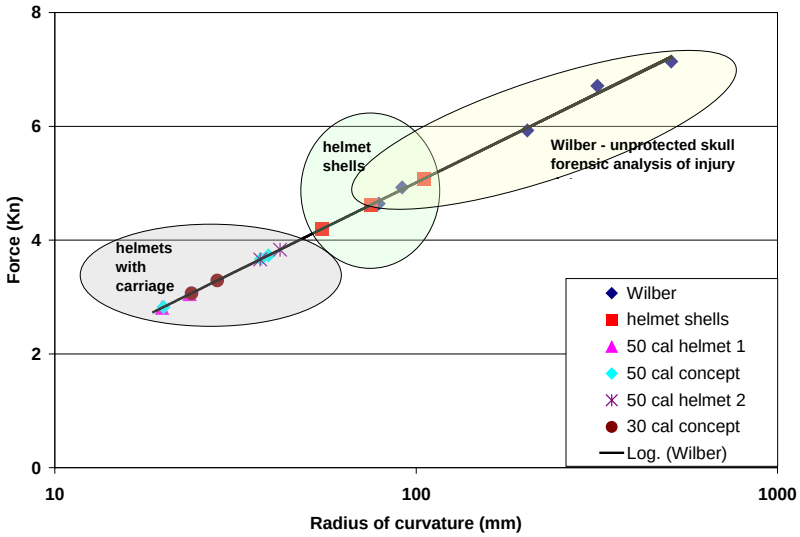

Figure 2 – Force vs Radius of Curvature for Skull Fractures

When compared with the skull fracture loads reported by Wilber[4] the radii of curvatures measured from the ballistic impacts corresponded to force values of 4 to 5kN, figure 2. These force values and an average head weight (mass) of 5kg were used to derive acceleration ($F = m \times a$) which was found to be 100g. This result implies that the skull could be fractured by BABT with accelerations of approximately 100g supporting Slobodik[6] whose investigation into US Army helicopter crashes concluded that the 400g limit of acceleration for survivability should be reduced to 150g.

HEAD FORM DEVELOPMENT AND CALIBRATION OF SENSORS

To quantify and measure the impact forces a simple aluminium head form shape was fitted with a 9031A Kistler® force transducer and film sensors, figure 3a and 3b. These film sensors are very reasonably priced so for testing could be considered

Figure 3. (a) Aluminium head form (on stand) showing position of Kistler® transducer b) Sensor attached to Aluminium head form and Hybrid 3 neck

as a one test disposable item. The film sensors were more flexible and easy to attach to the head with tape. It was hoped that the film sensors would be able to pick up an average force for over a fixed area throughout the impact event. The 25mm sensor pad is positioned in the centre of a flexible polymer film sandwiched between two layers of foam. The sensor samples at 250 kHz in 30ms and the output is an average of the applied force across the sensor. To validate the force output from these sensors a calibration method was developed their outputs were compared with the force output from a calibrated[6] 9031A Kistler® compression load cell fitted into an Imatek IFW10 accelerated drop weight machine, figure 4a and 4b.

To compare and understand the effect of averaging of the applied force over an area three striker shapes were used to investigate the application of load over different surface areas. In the initial tests an aluminium base plate simulated the effect of the aluminium head form which would be used in the ballistic tests. Force, time, velocity and displacement during an impact event are measured by the Imatek IFW10 and as the mass of the falling weight is known energy to fail can be determined. No electronic smoothing or signal processing filters were applied to the data as these can reduce the peak force values.

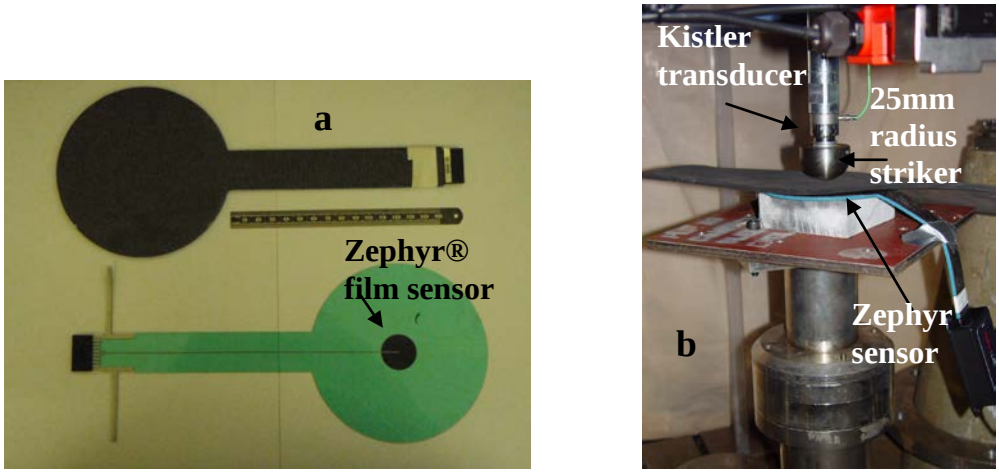

Figure 4. a) Film sensor inner and protective foam cover, b) Striker assemblies and Drop tower calibration set up showing the 50mm radius striker fitted.

The impact velocity for all drop tower tests was $1ms^{-1}$ and the sensors measured between 50% and 70% of the applied load. This difference may be attributed in part to some of the forces being dissipated by the protective foam layers at either side of the sensor. Peak force values for the 25mm striker were double those for the 50mm and 15mm strikers. The measured force per unit area is averaged by the Zephyr® sensors this indicates that for this striker the impact forces were distributed over a smaller contact area, figure 5. High peak forces over a short time would be expected from ballistic impact upon a helmet, therefore this striker was selected for calibration of the outputs from Zephyr sensors, transducer and accelerometers in the head form.

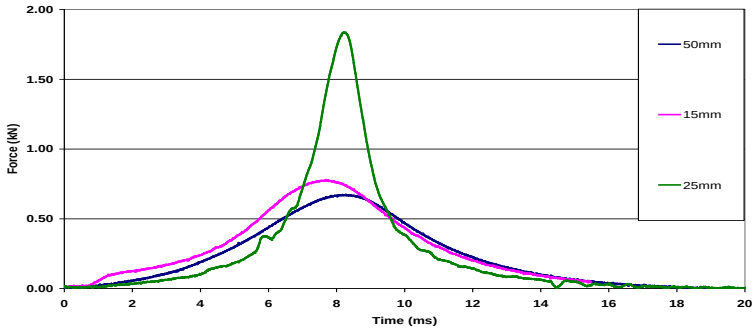

Figure 5. Comparison of Force vs Time drop tower traces of the three striker shapes

CALIBRATION OF THE HEAD FORM TRANSDUCER

The 9031A Kistler ® transducer in the Imatek IM10 drop tower was used to calibrate the force responses from the Kistler® 9031A transducer fitted into the aluminium head form mounted onto a hybrid III neck, figure 3a. Figure 6 shows the force responses from the head form transducer and these correlated with the force being applied, figure 6.

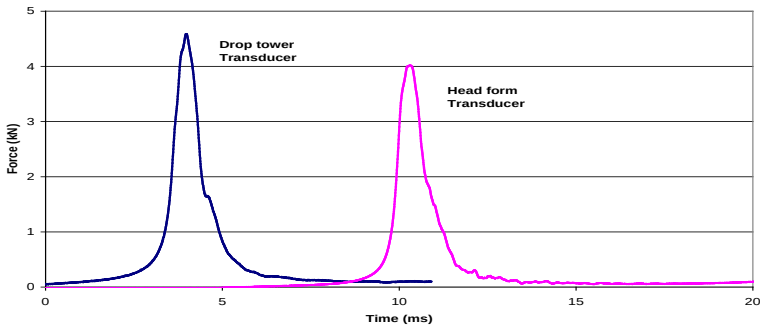

Figure 6. Comparison of force outputs from Kistler® transducer fitted in Imatek drop tower and head form.

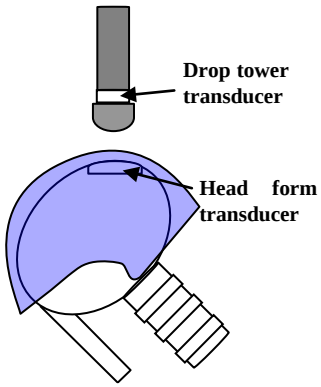

Figure 7. Diagram of head form positioned for drop tower impacts

The drop tower tests continued with helmets fitted onto the head form as illustrated in figure 7, to calibrate the force transducer outputs with the three accelerometer outputs. Using the least squares method the x, y and z axes accelerometer outputs were then summed to give a figure for total acceleration and multiplied by the mass of the head (4.82kg) to derive a force value to check the validity of the outputs from the system.

Figure 8 compares the peak force from the drop tower transducer (the applied force) of 7 to 8kN with the peak force of 1.8kN measured by the head form transducer behind the helmet and shows the effectiveness of the helmet shell and padding in attenuating the force.

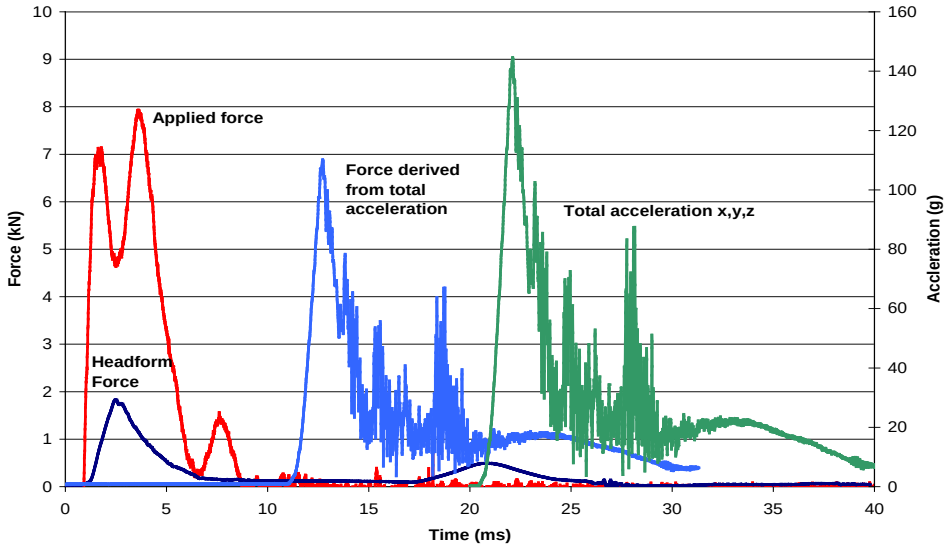

Figure 8. Comparison of Transducers and Accelerometer outputs

The total acceleration of 140g is under 400g limit of acceleration for survivability and correlates with Slobodik[7]. The force trace derived from total acceleration data verifies the applied force data. The time history of this test correlates with that seen in work on blunt impact and the 15-20ms duration of the force pulse is typical of time durations recommended for the calculation of head injury criteria (HIC).

BALLISTIC TESTS

After calibration both the headform transducer and film sensors were used to measure forces and accelerations from back face deformations behind two different helmet types and aramid helmet shells fitted with carriage systems. All shots imparted a load centrally on the sensor. The shots were positioned over the mitigation pads on the front right or front left temple or centre back with this padding in direct contact with the head form. No standoff distance from the head

form was allowed and no skin or tissue simulant was placed over the transducer impact area. These test conditions combined with rigidity of the aluminium head form transducer mounting would measure the magnitude of the forces of a "worst case" impact scenario. Without extra foam protection some of the film sensors sustained irreversible damage during ballistic impact so a limited amount of data was collected from those tests. Although the response time of the sensors is fast enough for ballistic impact events the sensors will need further development to improve their robustness during the impact event.

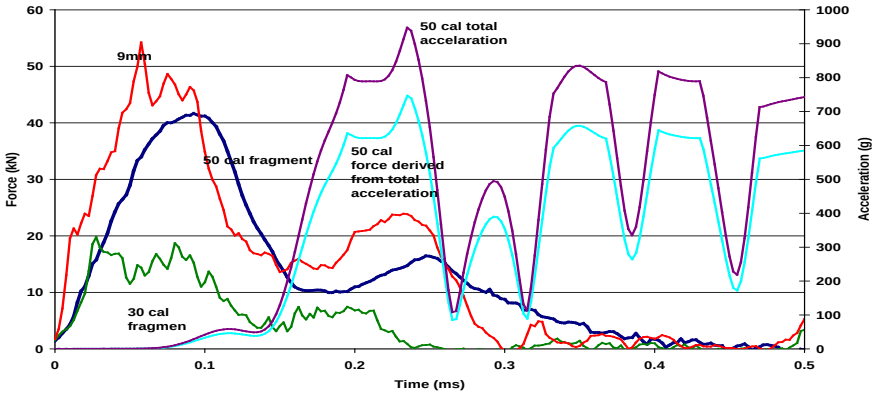

Figure 9. Comparison of force traces from head form transducer of 30 cal, 50 cal and 9mm shots

Force traces from 9mm, 50cal and 30cal fragments impacting the head form transducer and the order of severity of the impacts on helmet shells are compared in figure 9. Each shot was placed on the helmet so that the transducer would be correctly loaded along its centre axis. The smaller 30 cal fragment (2.84g at 473ms^{1}) imparted an impact energy of 318J and consequently had a lower peak force compared to the 540J from the heavier 50 cal fragment (13.39g at 284ms^{-1}) and the 666J from 9mm (8g at 408ms^{-1}) round. The force trace derived from the total acceleration of the 50 cal shot is also shown and verifies the force data from the head form transducer. The force readings recorded from the 9mm and 50 cal impacts are high and the peak acceleration of 940g from the 50 cal impact is more than double the accepted 400g limit. The time to reach peak force and acceleration and the duration of the pulse is short at typically 0.05ms or less. High speed video of the event showed that upon impact the helmet deformed applying a force to the transducer, the helmet material then rebounded and resonated with the oscillations gradually being absorbed by the helmet, head form and neck movement. No acceleration of the neck was seen during the short duration of the ballistic impact event. Measurements from the high speed video showed the acceleration of the head and neck began at 0.69ms. The complete unfiltered time history of the head impact and neck accelerations of a 9mm shot as they gradually decrease over 5ms is shown in figure 10.

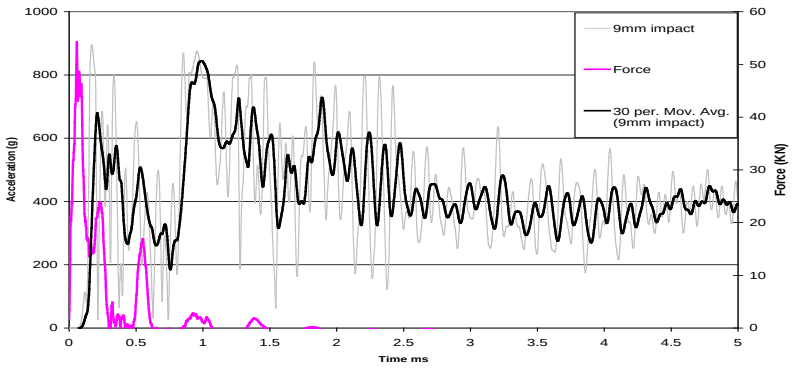

Figure 10. Force vs time and acceleration vs time histories of the head impact and neck accelerations from a 9mm impact

This time history correlates with previous work by Bass et al [1] on 9mm impacts on helmets mounted onto a modified hybrid III head form. A 30 point moving average filter was applied to the accelerometer data to resolve the major peaks in the signal for comparison with the Force signal but the first peak is reduced dramatically by filtering. Low pass digital filtering also reduces peak force levels so the filtering process must be used carefully or meaningful data could be lost.

SUMMARY AND FURTHER WORK

This initial work showed the head form was robust and could be suitable for simple ballistic tests as the peak force results were repeatable. The duration of the time of the ballistic impacts correlated with high speed video and similar work by other research groups[1,2,3] as did the timings to accelerate the neck. The 0.05ms duration of the peak force imparted to the head from ballistic impact is at a much higher rate than the 15.0ms duration rate accepted as suitable for the HIC calculations used for blunt impact. This concurs with Bass[1] who found that current HIC is not the best method to predict likely levels of head injury in ballistic events. Further work will be necessary to investigate compliance issues due to the rigidity of the head form when compared with more biofidelic systems.

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2008-09-22T00:00:00Z

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