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Unpacking blast fragment and pressure wave contributions to target deformation and failure

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14. ABSTRACT

The research team was only able to recruit two MSc students starting this project in 2021, but both have made decent progress and should submit dissertations for examination within the normal 2 years of our MSc program. They recruited a third student in 2022, whose project will continue into 2023 - nominally outside the project timelines, but they have ensured a portion of the budget is set aside to support this. The results to date from the MSc students in their second year are promising, showing consistent trends with simulations - though uncertainties in the target material fracture model leaves room for improving the prediction of penetration or rupture. As the focus of the third MSc, due for completion in 2023, will produce high strain rate tensile data and improve our fracture estimates, they are hopeful of improving the blast and fragment impact simulations in future.

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University of Cape Town

FA8655-21-1-7012

Unpacking blast fragment and pressure wave contributions to target deformation and failure

Project Completion Report

Principal Investigator:
Dr Reuben Govender (UCT)

Contributing Staff:
Prof. Steeve Chung Kim Yuen & Dr Trevor Cloete
Reporting Period: March 2021 - Nov 2023

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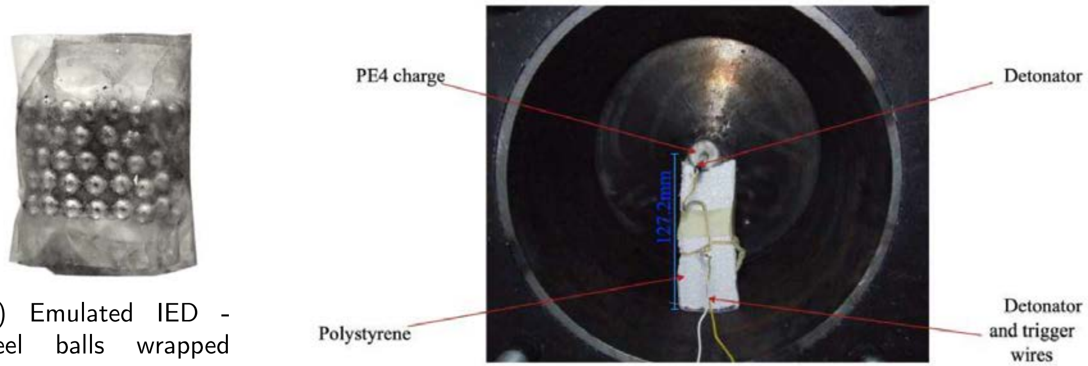
1 Introduction and Background

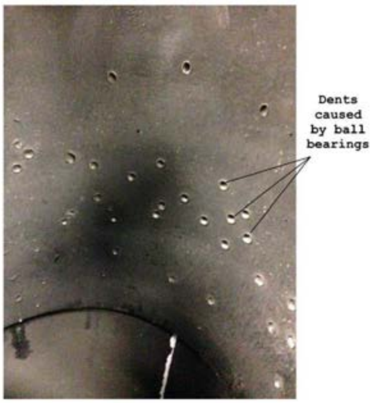
The response of armoured structures to either pure projectile impact or explosive gas loading has been well studied and reported on. However, most real world explosion events, particularly those involving Improvised Explosive Devices (IEDs), mean the target is subjected to impact from shrapnel or fragments and the blast wave in rapid succession. There is relatively little open literature on combined blast wave / projectile impact loading. This project seeks to address aspects of combined blast and projectile loading on steel targets, building understanding of relative contributions to permanent deformation and/or penetration of the target.

IEDs frequently include shrapnel in the form of bolts, ball bearings and other commonly available hard metal components, packed around or embedded in the explosive charge. The shrapnel velocity and spread of a real world IED is more likely to be a randomised distribution over a wider range, than designed as focused attack on a very specific target. In the interests of better understanding the combined effect of the blast wave and shrapnel damage,the Blast Impact and Survivability Research Unit (BISRU) at the University of Cape Town (UCT), has employed laboratory scale blast experiments using a limited number of steel ball bearings embedded at specific locations in a Plastic Explosive Composition 4 (PE4) charge. BISRU has a Blast Chamber which is licensed for detonation of up to 75 grams of PE4. BISRU's first set of experiments to emulate IED damage were conducted by MSc student Gi-Ah Kang [1]. Kang's experiments involved multiple steel ball bearings embedded circumferentially in a cylindrical PE4 charge (Figure 1a). The explosive was detonated inside a low carbon steel tube, shown in Figure 1b, with the indentation pattern (Figure 1c) providing information on the dispersal of the steel balls. Kang inferred the balls' impact velocity from indentation depth and simulations using the AUTODYN hydrocode, but didn't conduct independent indentation or material characterisation studies to confirm this.



(a) Emulated IED - steel balls wrapped around PE4

(b) Emulated IED inside steel witness tube

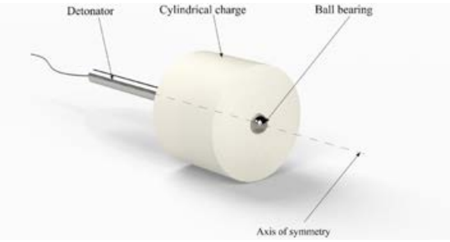


(c) Indentation on witness tube post detonation

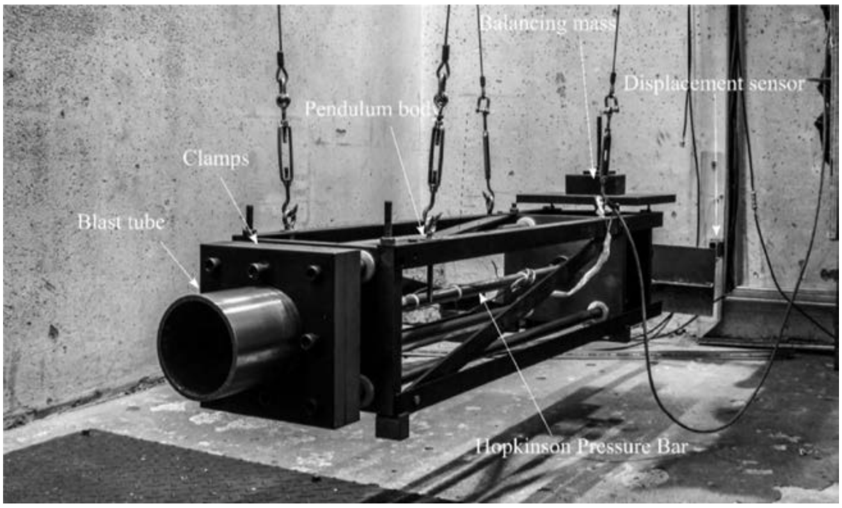
Figure 1: Kang's simulated IED experiments [1]

To better understand the velocity of the fragments, Kang's multiple ball charge was simplified by Ruixuan Qi to a single steel ball on the front flat face of a PE4 cylinder, detonated from the back flat face (Figure

2a). Qi conducted blast experiments where the ball was directed towards a Hopkinson Pressure Bar (HPB) mounted on a ballistic pendulum (Figure 2b), permitting an experimental measurement of average ball velocity between the change and witness plate. Qi further employed gas gun experiments on aluminium witness plugs to better correlate the impact velocity of the steel ball with the indentation measured after the blast experiment.



(a) Single ball emulated IED



(b) Ballistic pendulum instrumented with HPB

Figure 2: Qi's charge configuration and ballistic pendulum arrangement

Observation of Kang and Qi's experiments, along with that of photographs of real world IED damage, made it clear that the ball or shrapnel was seldom impacting the target perpendicularly. It was far more common for the impact to be oblique. While the effect of oblique impact has been studied for purely projectile impact (for example [2], [3]), little has been published where the projectile has been explosively driven and impact is oblique. Furthermore, the effect of the ball or shrapnel being embedded within the explosive (rather than sitting at the surface) had not been reported on. This gave rise to two MSc projects that were supported by this funding:

- Response of a Structural Steel Target to Foreign Objects embedded at varying depths in an Explosive Charge
- Response of a Structural Steel Target to Oblique Fragment Loading

The simulation of steel targets to blast or projectile impact loading is greatly improved by having plasticity and fracture or damage models that have been characterised over a range of strain rates. BISRU has a Tensile Split Hopkinson Pressure Bar (TSHB) that enables tensile loading of sheet metal specimens at strain rates of approximately 300 to 1000 $/s$. The BISRU TSHB uses a novel tapered thread fixture with a lobed specimen, shown in Figure 3. This fixture ensures the specimen is positively located, avoiding the slippage associated with friction grips, while minimising the impedance mismatch associated with larger gripping fixtures. Prior BISRU studies by Weyer et al. [4] used Domex 355 specimens with flat, notched and grooved gauge sections to investigate rate dependence of failure strain, under a variety of stress triaxiality conditions.

(a) Tapered thread specimen fixture

(b) Lobed sheet metal specimens

Figure 3: TSHB fixtures and specimens

The initiation of ductile metal fracture has long been understood to depend on void growth and coalescence under the action of stress triaxiality (for example [5]) and Lode angle (for example [6].

In order to experimentally study void growth and coalesence for quasi-static experiments, it is very simple to stop the loading at the desired specimen deformation. However, at impact strain rates, it is non-trivial to arrest deformation as the test is not actively controlled after release of the striker. Nonetheless, SHPB experiments can make use of momentum trapping to ensure the specimen is subjected to only a single high strain rate loading event of a controlled magnitude [7], permitting recovery of the specimen prior to fracture. This practice is fairly well developed for compression SHPB experiments, with nested tandem momentum traps having been implemented at BISRU for prior compression studies [8]. However, the application of momentum trapping to tensile SHPB experiments is a less mature technique. As the tensile loading mechanism employed by BISRU for prior TSHB studies [4] did not allow for momentum trapping, this gave birth to a third MSc project that was supported by this funding, specifically:

- Development of a system for high strain rate interruptible tensile tests

We believe these three MSc projects have generated good quality experimental data as well as built platforms that will support future, more detailed investigation of combined blast and fragment loading using a blend of numerical simulations and experiments.

2 Postgraduate Student Projects

2.1 Foreign Objects Embedded at Varying Depths in an Explosive Charge

MSc Student: Matthew Hoare
Primary Supervisor: Prof. Steeve Chung Kim Yuen
Co-supervisors: Dr Reuben Govender and Dr Trevor Cloete
First Registration: March 2021
Status: Dissertation examination complete, graduation December 2023

Qi [9] had successfully measured the impact velocity of ball bearings (as a controllable surrogate for fragments), but only for balls on the surface of an explosive charge. This project investigated the dependence of the depth of the ball inside the charge, with the following research objectives:

1. Investigate how the depth of a ball bearing embedded at different placements along the cylindrical axis of a explosive charge affects the ball bearing's velocity and the damage the combined load inflicts to a steel target plate.

2. Investigate how the length of a cylindrical charge with a constant diameter affects the damage the ball bearing inflicts to a steel target plate.

3. Formulate a numerical model to replicate a blast driven ball bearing for varying depths and charge lengths at a target plate to validate the experimental data and gain further data.

4. Conduct a parametric study, using results from both the FEM simulations and practical experiments, comparing the length of the charge and embedded ball bearing placement in the charge along the cylindrical axis to permanent deformation.

Figure 4 shows a sectioned view of the CAD model of the experimental rig. A ball bearing was embedded at a variable depth in the explosive charge, that propelled the ball towards the steel target plate. The ball impacted an aluminium witness plug, which in turn transmitted a stress wave to a pressure bar behind the target. This allowed two metrics for ball velocity, namely depth of penetration and time between the arrival of the blast wave and the ball impact.

Similarly to Qi, Hoare conducted experiments using a two stage gas gun to propel a steel ball towards aluminium witness plugs. The gas gun indentation experiments enabled an independent correlation of indentation and ball velocity just prior to impact, which was measured using high speed video. Hoare also conducted experiments with deformable steel target plates (2mm thick Domex 700 alloy), where prior experiments had used rigid steel target plates, subjected to a combined load from an explosive charge with a single embedded steel ball.

Figure 5 presents the simulated trends in ball impact velocity as charge mass and ball placement (within the charge) are varied, using the ANSYS Autodyn hydrocode. Hoare's simulations confirmed Qi's observation that the blast pressure wave reaches the target plate first, followed by projectile impact at a slightly later time. It is apparent that a ball which is very lightly embedded in the explosive surface achieves the highest velocity. As depth of placement is increased, impact velocity falls sharply, with a centrally buried ball near stationary.

Figure 6 shows the pressure bar's axial stress history recorded in a typical experiment, with the spikes corresponding to the first arrival of the blast wave, a reflected wave and the largest spike being the impact of the ball. While the magnitudes of the stress differ somewhat from the simulations, the peaks do allow reasonably precise measure of Time of Arrival for the different loading. Table 5 presents a preliminary comparison of simulated Time of Arrival of the ball with the target, against experimental values inferred from

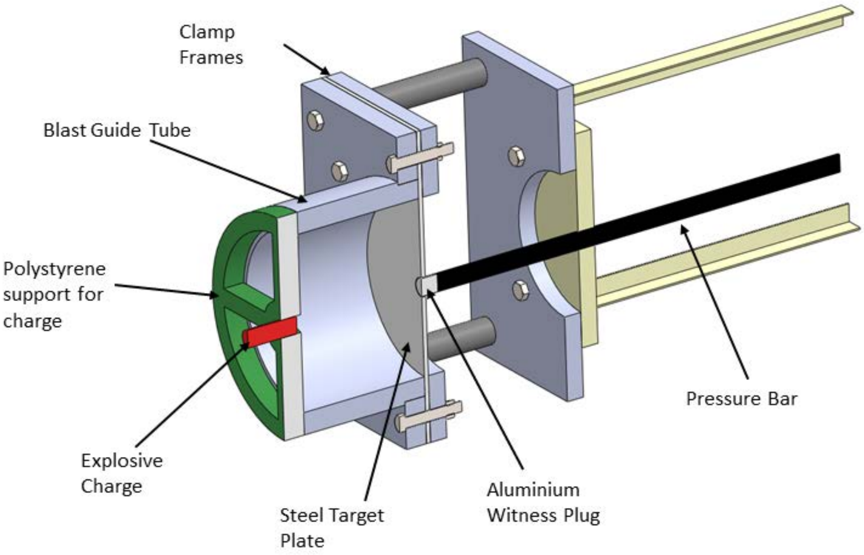


Figure 4: Ballistic pendulum for measuring fragment velocity

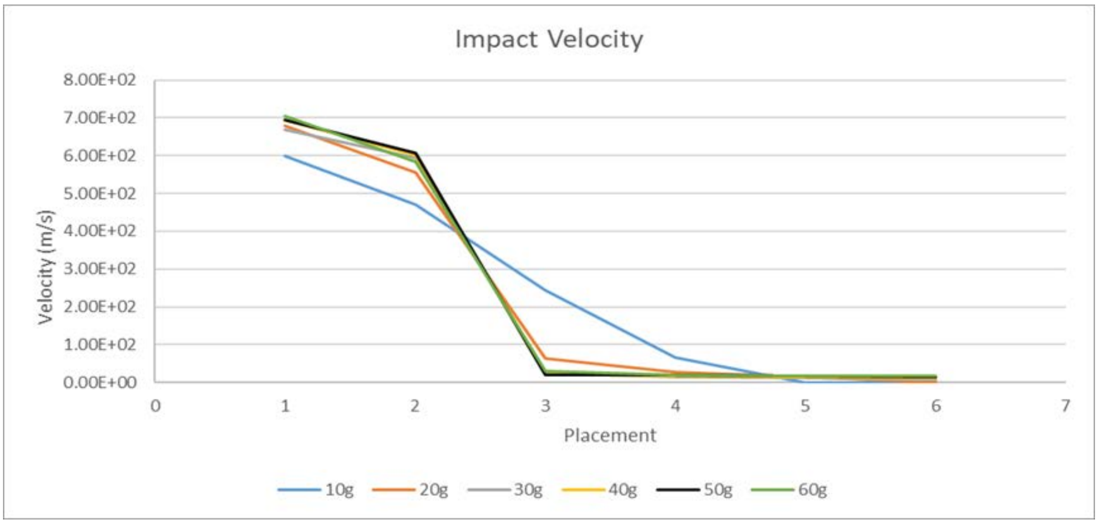


Figure 5: Simulation results for ball impact velocity

Table 1: Comparison of ball impact velocity for simulations and experiments

Charge Mass (g)	Time of Arrival (ms)		
	Simulation	Experiment	Difference
20	0.214	0.231	-0.017
30	0.227	0.238	-0.011
30	0.227	0.211	0.016
30	0.227	0.214	0.013

the pressure bar histories. There is acceptable variation for repeat experiments under identical conditions and reasonable agreement between simulation and experiments.

The combined loading experiments showed a localised indentation and cap where the ball impacted (Figure 7a), superimposed on a global deflection largely associated with the blast pressure loading (Figure 7b). The combined blast and impact load showed a greater deflection than the sum of separate ball bearing impact and blast deflections. While this was expected from the literature, it contradicted the experimental

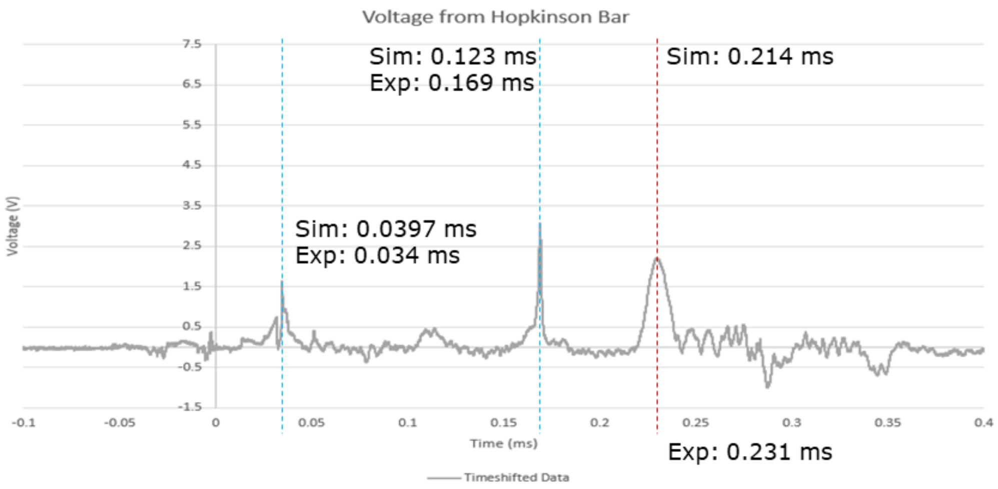
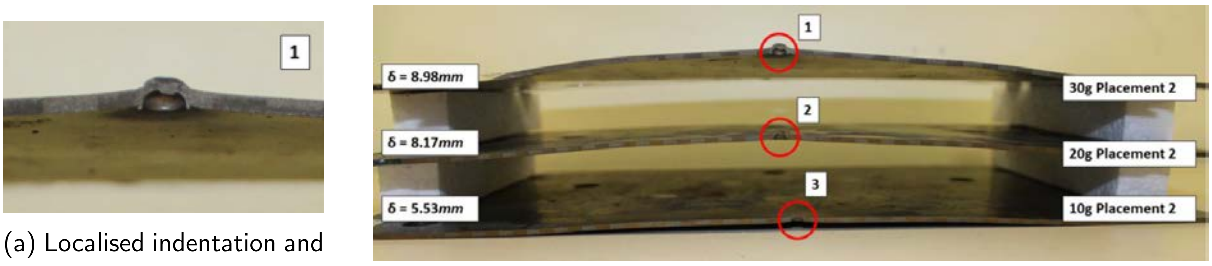


Figure 6: Pressure bar history, showing arrival of blast waves and ball impact

result where the cap deflection from the two stage gas-gun impact test was less than the cap deflection from combined and impact tests. So even though the cap deflection from combined blast and impact testing was less than the cap deflection from impact velocity tests, the combined blast and impact loading exhibited greater global deflection. As the 2mm thick Domex 700 steel target plate in this study is still relatively strong, it was not possible to achieve complete perforation of the target blate in either gas gun or combined blast loading, given the operational limits of the BISRU facilities. Hoare recommended that future studies consider a target plate of lower thickness or a weaker material, which would enable both complete perforation and larger global deflections within the loading limitations of the gas gun and blast chamber. This would reduce uncertainty in the indentation and cap measurements and help clarify which part of the combined load was doing greater damage.



(a) Localised indentation and cap

(b) Global deflection of target plate

Figure 7: Sectioned target plates after combined loading

The full text of M. Hoare's examined MSc dissertation may be found at: https://drive.google.com/file/d/1ExXqBjFWIKcGLW2JiWuQlZQY2enNviKn/view

2.2 Oblique Fragment Loading

MSc Student: Pierre van der Merwe
Primary Supervisor: Prof. Steeve Chung Kim Yuen
Co-supervisors: Dr Reuben Govender and Dr Trevor Cloete
First Registration: March 2021
Status: Dissertation examination complete, graduation December 2023

In the real world, both fragments and blast waves are unlikely to be travelling perpendicular to the target, but at some angle. The effect of oblique impact between projectiles (whether driven by gas guns, or conventional firearms) and target plates has been well reported in the literature (for example [2, 3]). The effect of oblique shock waves [10] on target plates been investigated, as well as blast loading on oblique targets [11]. However, the effect of combined oblique blast waves and projectile impact remains sparsely documented, and is the primary topic of this MSc investigation. The specific aims of this project are:

1. Investigate oblique impact of a gas-driven ball bearing on a metal plate.

2. Investigate oblique impact of a blast-driven ball bearing on a metal plate.

3. To formulate a numerical model to simulating the influence of the oblique angle on the metal plate and the ball bearing, driven by an explosive blast.

The target plates for this project would be 2mm thick Domex 700 steel plates, to allow for continuity with the parallel work conducted by M. Hoare.

Figure 8 shows a CAD image of the experimental rig to incline the target plate relative to the gas gun barrel, as well as the protective catch box surrounding this. The side panels of the catch box are polycarbonate, allowing for high speed video of the projectile on the proximal side of the target. Impact velocities can be estimated from the high speed video. Gas gun driven projectile impact experiments were conducted from perpendicular impact up to a 45° inclination, with ball velocities ranging from 150 to $700\,\mathrm{m\,s^{-1}}$.

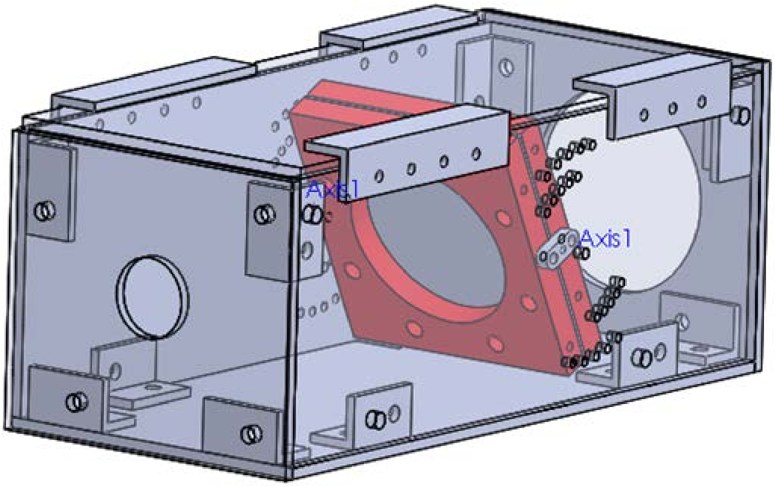


Figure 8: CAD model of inclined target clamps and catch box

The oblique blast experiments used the same cylindrical charge with single ball as used by M. Hoare, but with a polystyrene frame to support the charge at an angle to the target plate, as shown in Figure 9. The position of the charge was varied with inclination, such that the ball should strike the target plate centrally.

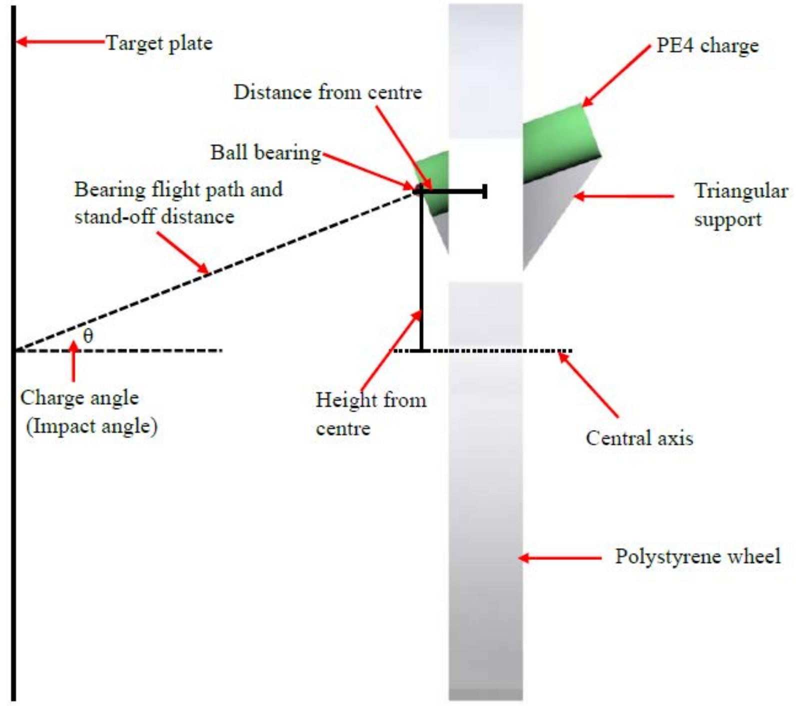


Figure 9: Schematic of inclined charge and target plate

Due to constraints with the ballistic pendulum that supported the target plate at a fixed stand-off distance of $150\,\mathrm{mm}$, the maximum inclination that could be investigated in blast experiments was $25°$.

The gas gun driven experiments showed that the crater formed by the ball started as circular for the perpendicular impact, and becoming increasingly elliptical as the inclination of the target plate was increased. While measurements of the crater aspect ratio suffered from some uncertainty (Figure 10) the trend towards an ellipse was clear. Similarly to the experiments conducted by M. Hoare, the gas gun was unable to achieve sufficient velocity for complete perforation of the target plate.

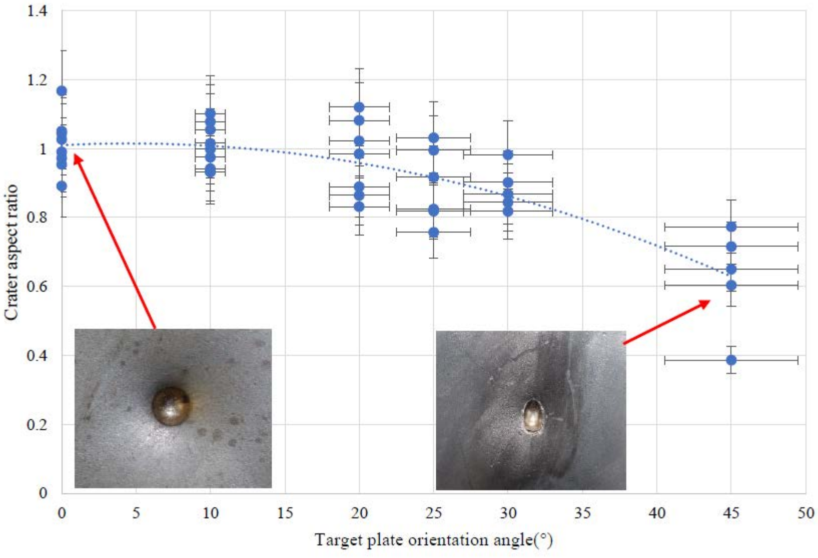


Figure 10: Evolution of crater aspect ratio with changes in impact angle

Of the 14 blast experiments, 10 resulted in complete perforation of the target by the ball with the remaining 4 showing the ball either indented in the target or rebounding after leaving a significant crater. For the targets with incomplete perforation, it was possible to measure both a global dome deflection and a local cap deflection (similarly to M. Hoare's work), whereas complete perforation meant only the global dome deflection could be measured. The change in deflection as the angle of charge was varied is shown in Figure 11. The global deflection was smaller for perpendicular impact and smaller angles (5° 10°). This was attributed to rapid onset of shearing and complete perforation. At larger angles, the larger global deflections suggest that with oblique impact and sliding between ball and target, more energy could be transferred from ball to target before localised shearing was triggered.

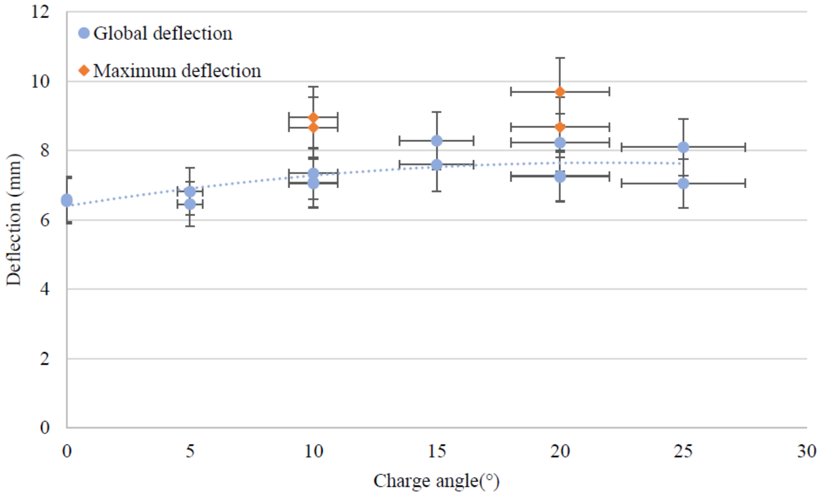


Figure 11: Global and local deflection in combined blast experiments for different orientations

The full text of P. Van Der Merwe's dissertation may be found at: `https://drive.google.com/file/d/1Tk6wf9n8QKGc2qUHr-3R7uJuof0ScVs8/view`

2.3 Interrupting High Strain Rate Tensile Tests on a Hopkinson Pressure Bar

MSc Student: Malcolm Thomas
Primary Supervisor: Dr Reuben Govender
Co-supervisors: Dr Trevor Cloete
First Registration: Feb 2022
Status: Experiments complete, first draft of dissertation under review, expected to submit dissertation for examination end Jan 2024

Material stress-strain response across a range of strain rates is essential to more accurate simulation of target deformation and ultimately rupture. BISRU has already made use of a Tensile Split Hopkinson Pressure Bar to characterise similar target materials in strain rate ranges from 10^2 to $10^3/s$, described in [4] and illustrated in Figure 12. Interrupted tensile tests, where specimen deformation is halted prior to fracture, are useful for tracking damage evolution and the onset of fracture. It is relatively straightforward to interrupt a quasi-static tensile test. However, for a high strain rate test reliant on wave propagation, some sort of momentum trapping system is needed to ensure that reflections of the stress waves don't cause repeat loading of the specimen. Past BISRU work has used a tandem momentum trap [8] for compression SHPB tests to allow for consistent momentum trapping and deformation interruption, without needing the operator to set precise gaps or "tune" for each specimen.

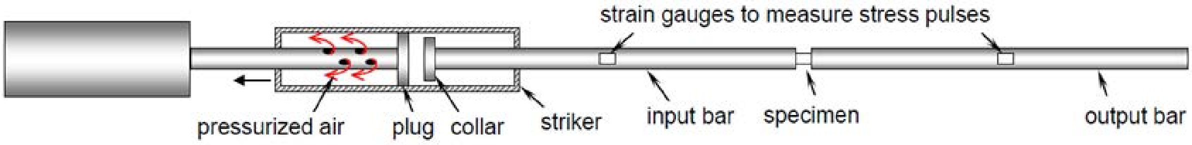


Figure 12: Schematic of Tensile Split Hopkinson Pressure Bar

The major research goals for this project are:

1. Adapt the tandem momentum trapping concept for tensile SHPB tests.
2. Design and build a modified tensile gas gun
3. Conduct interrupted high strain rate tensile tests on sheet steel specimens to demonstrate proof-of-concept

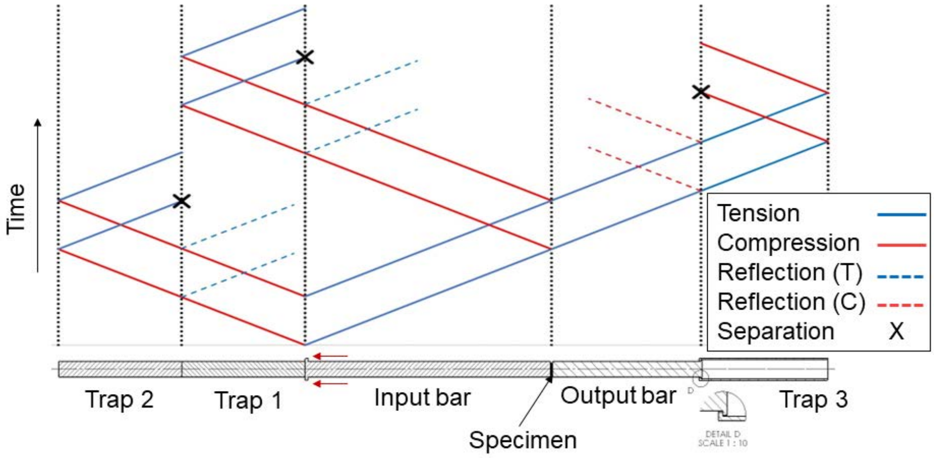
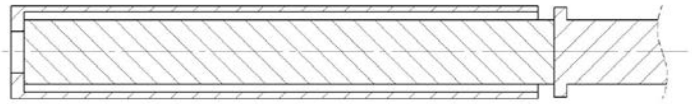


Figure 13: Lagrange Diagram of Wave Propagation using Tandem Momentum Trap

Figure 13 shows the wave propagation in the tensile tandem momentum trap concept, illustrating how momentum is "trapped" in the successive bars, preventing a reflected wave from re-loading the specimen. Thomas has also implemented the nested tandem momentum trap concept (Figure ?? which represents significant space saving over the traditional in-line tandem traps (Figure 14a). In any HPB testing, saving space for ancillary components translates to more room for the input and output bars, thereby enabling a wider range of loading for future testing.

(a) In-line tandem traps



(b) Nested tandem traps

Figure 14: Configurations of tandem momentum traps

Figure 15 shows the success of the nested tandem momentum traps when applied to the input bar of the TSHB. With the traps in place, the reflected wave is less than 1% of the amplitude in comparison to the same test without the traps. This test was conducted without a specimen in place, as it is possible to load the input bar on its own. However, to load the output bar in tension it is necessary to have a specimen loaded. Testing with a large cross section, effectively rigid, specimen didn't prove fruitful as the much smaller impedance difference meant the specimen was storing a large amount of elastic strain energy. The unloading of the specimen lead to this energy being transmitted to both input and output bars, creating spurious waves. However, testing with a specimen of similar cross section to that used by Weyer has yielded much more promising results, as shown in Figure 16. Both input and output bars show very small waves after the initial loading. While the momentum trapping hasn't functioned perfectly, the amplitude of the remaining waves is sufficiently small that further specimen deformation should be negligible.

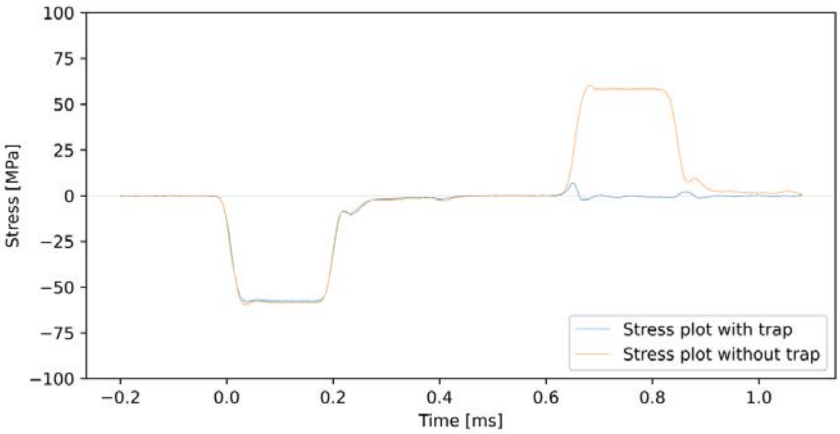


Figure 15: Input bar momentum trapping

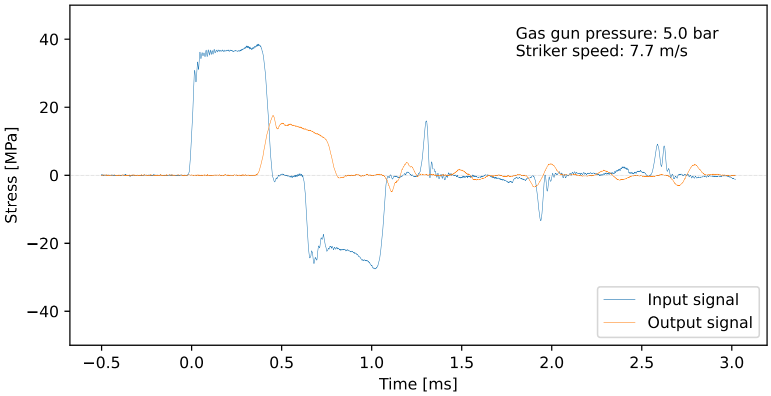


Figure 16: Momentum trapping for both input and output bars

3 Concluding Remarks

We were only able to recruit two MSc students (M. Hoare and P. van der Merwe) starting this project in Feb 2021, who opted to pursue the two blast loading projects. Ideally, we would have wanted one of these students to pursue the Tensile SHB project to enable data from this to feed into the others sooner. However, neither of the students recruited had suitable design skills to tackle the SHB project. We recruited a third student (M. Thomas) in Feb 2022, who did have appropriate design skills. Hence the three projects were somewhat misaligned on timelines. Of the two students who began in Feb 2021, M. Hoare submitted his dissertation for examination at the end of Jan 2023 (inline with the two year norm for our programs), while P. van der Merwe submitted his dissertation in July 2023 (one semester delayed). M. Thomas has completed his experimental work and is analysing his final data set, and is on track to submit in Jan 2024, which will be the normal two years since he first registered.

The blast loading projects have partially addressed some of the research questions. It is clear that in the absence of any confinement of the explosive charge, the blast pressure wave will travel faster than the embedded projectiles and therefore causes the initial loading of the target plate. While both the gas gun and explosive experiments resulted in ball velocities in the region of 400 to 700 m/s, these were insufficient to cause complete perforation of the 2mm thick Domex 700 steel target. This leaves the question as to whether a fragment induced perforation will exacerbate or mitigate the deformation due to the blast wave, as an open research question to be addressed in future research.

The adaptation of the Tensile SHB gas gun to include nested tandem momentum traps on the input bar and a single nested trap on the output bar has proved successful. The initial experiments indicate that the specimen is subjected to a single high strain rate loading event. At present, the achievable strain rate and maximum deformation are coupled. Future planned research includes manufacturing a range of strikers which will allow decoupling of strain rate and maximum deformation. The experimental outputs of the next phase will provide high strain rate tensile tests, interrupted at various stages of deformation, to support microscopy investigation of void growth and coalescence, to inform improved damage models.

4 References

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