Gauging the Fireball: Simulation and Testing

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ABSTRACT

Little is known of the effects of combined blast and thermal loading on structures within an explosive fireball. This paper documents and discusses results from temperature, flux, strain and pressure gauges within a fireball of a conventional open arena trial using a 41kg TNT equivalent yield explosive. Plans to simulate an intense thermal fireball environment using a bespoke thermal tile are outlined.

INTRODUCTION

These arena trials were conducted to gauge data across the thermal spectrum from within the fireball of a conventional explosive; this data would set a benchmark for further tests and parametric studies to be undertaken. It was the intention not only to gauge thermal information from the fireball but also to observe the effects of the intense pressure and thermal loading on 2mm thick steel plates. Using the steel plates would allow differentiation between thermal and blast effects at a close distance from the burst centre. This data will become a vital part of a larger project involving the synergistic response of structures to both thermal and blast loading in extreme environments.

Conventional sized explosions do not often produce enough thermal output to considerably affect a structure. Therefore in order to quantify the thermal effect of larger explosions it is necessary to simulate such thermal yields. Much previous work has been undertaken in this field using various simulation devices and techniques to improve the accurate representation of the environment within a thermal fireball [1]. Throughout the development of these simulation devices problems such as disadvantageous combustion products and accurate fluence levels have been encountered. Therefore a bespoke thermal tile has been developed in order to eliminate the previous problems whilst producing a very high flux environment over a very short period of time

METHODOLOGY

Gauging the Fireball from a 41kg TNT eq. Explosive Event

Novel heavy structural boxes were designed and built in order to withstand the intense loading environment within the fireball. The boxes were fitted with a series of gauges and a 2mm thick steel plate. Previous experience showed that gauges closer than 4m from the explosion would have a high probability of not surviving the explosive event and that the fireball would extend no further than 8m radius. In order to provide a range of measurements the instrumentation was therefore set up at three radial locations; 4, 6 and 8m from the centre of the burst (Fig. 1a). The boxes were positioned at a height of 1m from the ground to the plate centre. The 2mm thick steel plates were bolted with a collar to a 12.5mm gauge structural steel box which in turn was mounted onto circular hollow sections (CHS). Thermal flux gauges, thermo-couples, pressure gauges, strain gauges (on steel plates) and temperature indicating labels were attached to the boxes.

Due to the volatile and unpredictable nature of the environment within the fireball it was necessary to use several types of gauges strategically positioned on the boxes in order to differentiate the effects. The thermal flux gauges and one set of thermo-couples were set up pointing vertically out of the top of the boxes, the (reflected) pressure gauges were positioned at the front of the boxes (adjacent to the plate) and the strain gauges and a set of second thermo-couples were positioned inside the boxes on the back of the steel plates (Fig.1b and Fig.2). The temperature indicating labels were adhered to several surfaces including the front surface of the CHS, the rear surface of the boxes, the inside faces of the boxes and the rear of the 2mm plates.

There were two sets of three boxes at each radial location. One set was fully instrumented with all the gauges and the other partially instrumented with just the temperature labels and pressure gauges at 4m and 8m, and no instrumentation at 6m. For the first trial the instrumented boxes faced the blast with the non-instrument facing away. For the second upcoming trial the box orientation will be reversed. The objective behind the different orientations was to attempt to distinguish the effects on the steel plates due to pressure from those due to temperature.

Several high speed cameras were used to observe the propagation of the fireball over time. After the trial the plate deformations were recorded and several non-tested plates of equal thickness and strength were statically tested to determine their tensile strengths.

Figures 1a and 1b. Photos of Structural Boxes.

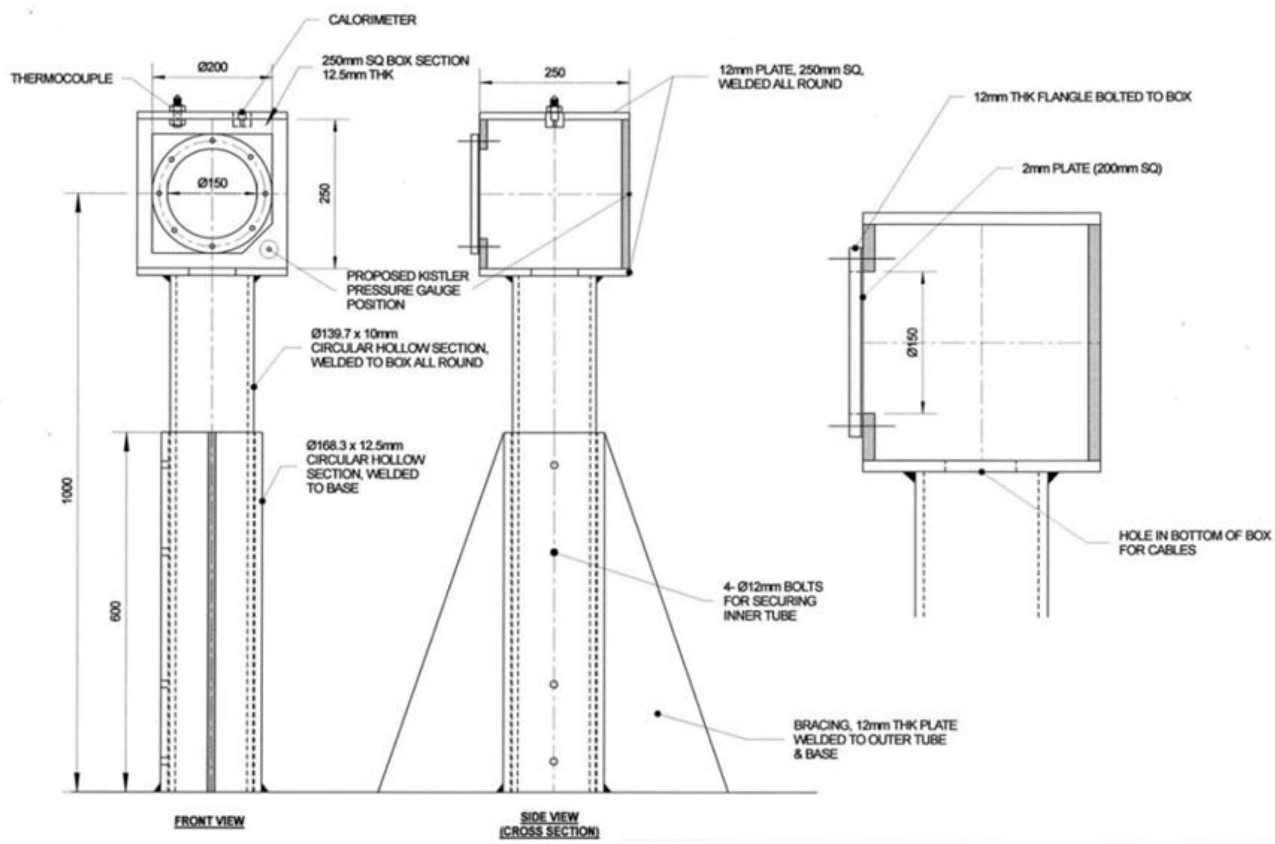

Figure 2. Drawing of Structural Boxes.

RESULTS AND DISCUSSION

Initial Observations

Immediately after the explosive event observations regarding the response of the plates and the temperature indicating labels were made. All three plates facing the blast had experienced deformations (0 to 11mm), the closest plate with the largest (11mm). There was no visible permanent deformation on the plates facing away from the blast. The permanent deflections on the steel plates facing the blast were caused mainly by the blast pressure; however, these initial observations do not show the deformation history that may have occurred in either set (see strain gauge data).

The temperature labels showed the spectrum of temperatures reached within the fireball, the highest (at 4m) was approximately 200°C, reducing to approximately 70°C at 8m. The labels also helped to show the peak temperature on the inside of the plates, 46°C at 4m. Despite the relatively slow response times of the temperature labels they allow a valuable comparison to be made with the thermo-couples and flux gauges. All the gauged structural boxes survived the trial, indicating that the fabricated boxes are fit for purpose for future thermal tile testing.

Three high speed cameras were directed towards the propagating fireball across the arena pad. Fig.3 shows a still from one of the cameras at 5.39msec after ignition. The cameras revealed the total life span of the fireball to be approximately 1sec and it reached its maximum at 24msec. The cameras show the fireball reaching the 4m and 6m boxes at approximately 3.2msec and 16msec but not expanding as far as the 8m box. The fireball extends just beyond the 6m box, leading to an approximate maximum diameter of 12.5m. The shockwave was at the fireball front at 0.8msec then subsequently overtook it (1.2msec). This data is used as a comparison to the gauge data.

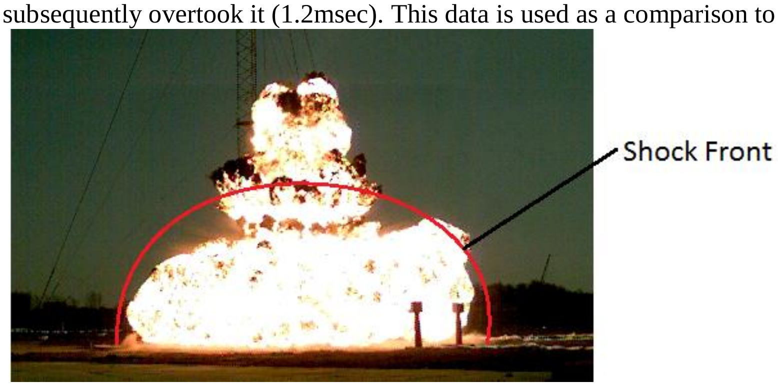

Figure 3. Fireball at 5.39msec after Ignition.

The steel used in the trials was Hot Rolled Steel BSEN 10111:DD11 (Steel for Forming). This steel was chosen due to its lower yield strength and higher ductility than a typical structural steel (275N/mm^2) hence ensuring the plates have a significant response to the explosive event. The 2mm steel plates were statically tested to determine the yield strength (YS), ultimate tensile strength (UTS) and Young's modulus (YM). The results of these tests showed a YS (0.2% Proof) of 162N/mm^2, an UTS of 266 N/mm^2 and a YM of 202x10^3 N/mm^2.

Gauge Data: Reflected Pressure

Two sets of reflected pressure gauges were positioned at 4m and 8m radial locations; one set facing towards the blast and the other facing away. Fig.4 shows the reflected pressure of the facing gauges at 4m over a short time frame at the start of the event. The peak recorded reflected pressure was 4040.45kPa, the impulse was 1.41kPa.s and the duration was 1.2msec with a time of arrival (TOA) of 2.95msec. The 4m gauge recorded a double peak pressure, which can be explained by several hypotheses:

- The second shock is from a reflected pressure of the ground which is more prominent due to its close proximity to the burst.
- The first shock is the main blast pressure and the second is the effect of ground shock on the gauge.
- The first shock is actually the shock from ignition of the initial explosive products, which disappears close to the burst and the second peak is the actual region of compressed air.
- The initial peak is due to 2kg of PE4 being ignited just before the 39kg of TNT.
- The second peak is from the reflection of the compressed air behind the front ("second shock").

Data from the second trial will help to resolve this phenomenon. The flat top of the peak pressure is due to the gauges only being able to record pressure up to 4MPa. Extrapolating the lines to form peaks the recorded pressure would be approximately 5MPa, which compares to the predicted reflected pressure of 5.4MPa at this range from Kingery and Bulmash [2]. For the second set of trials the pressure gauges will be re-calibrated to record over 4MPa.

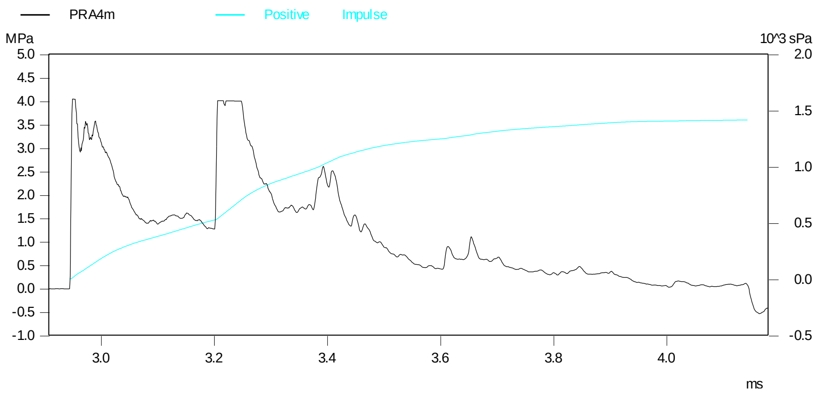

Figure 4. Reflected Pressures at 4m Facing Blast.

Fig. 5 shows the recorded reflected pressures at 8m facing the blast. The 8m facing gauges recorded a peak reflected pressure of 1237.6kPa and an impulse of 0.43kPa.s. The duration was 2.28msec and TOA was 8.34msec. Comparing these with predicted values for pressure (680kPa), impulse (0.403kPa.s), duration (7.47msec) and TOA (7.7msec), the pressure and duration differ considerably but TOA and impulse are similar. The double peak at 4m no longer exists, confirming that the phenomenon observed at 4m is restricted to areas very close to the centre of the burst.

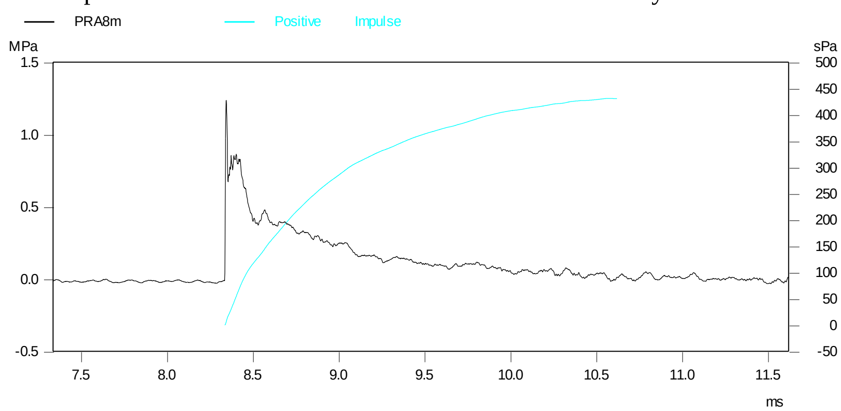

Figure 5. Reflected Pressures at 8m Facing Blast.

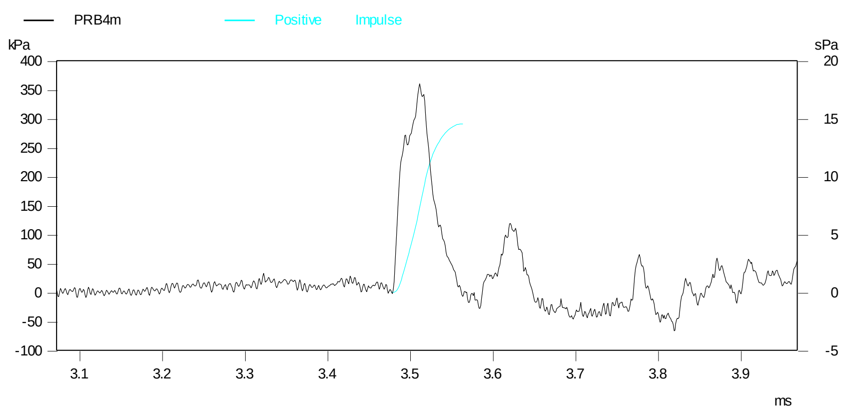

Figure 6. Reflected Pressures at 4m Facing Away From Blast.

Figs.6 and 7 show the reflected pressure at 4m and 8m facing away from the blast. At 4m the peak reflected pressure was 360.4kPa, impulse was 0.01kPa.s and duration was 0.09ms with a TOA of 3.48msec. At 8m the peak reflected pressure was 155.72kPa, impulse was 0.02kPa.s and duration was 0.45ms with a TOA of 9.03msec. After the initial impulse there are many later perturbations as the compressed air at the back of the box is reflected and diffracted.

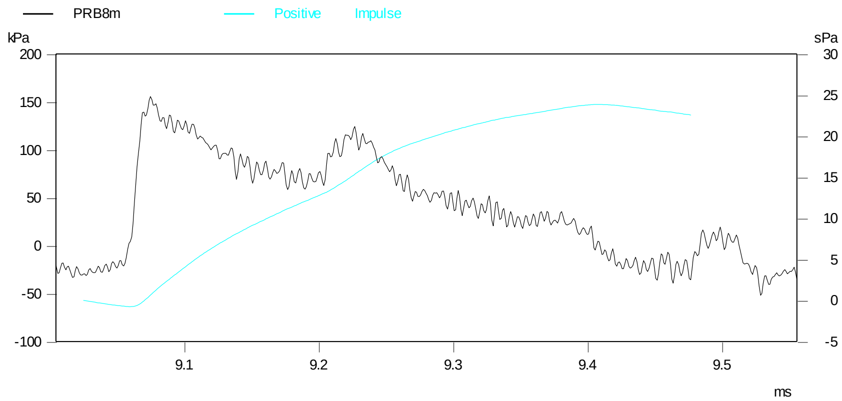

Figure 7. Reflected Pressures at 8m Facing Away From Blast.

Temperature (Thermo-Couples)
The varying temperatures across the fireball were measured using thermocouples placed inside and outside of the boxes. Fig. 8 shows the external recorded temperatures. An initial high temperature increase is followed by a low temperature drop into negative values. This event occurs at approximately 25msec, which is similar to the plots for flux and strain, where comparable rapid increases at approximately 25msec occur. An explanation for these extreme recordings is that a part of the explosive event caused an electrical disturbance to the gauge data at 25msec.

At 4m the temperature peaks at 480°C with a rise time of approximately 140msec. The temperature then slowly drops over several seconds. At 6m the peak temperature was 105°C with a rise time of approximately 410msec. At 8m the peak temperature was 74.5°C with a rise time of 480msec. The atmospheric temperature was 16.4°C at time of detonation; therefore the estimated time for the temperature at each box to return to this was 5.1sec at 4m, 9.6sec at 6m and 6.8sec at 8m. The temperatures recorded by the thermocouples are the temperatures of the thermocouples themselves not the actual air temperature. The rate at which the apparent temperature drops should therefore be taken as the cooling rate for the thermocouples. The external surfaces of the plates were assumed to be the same temperature. For the second trial the length of time recorded by the gauges will be increased.

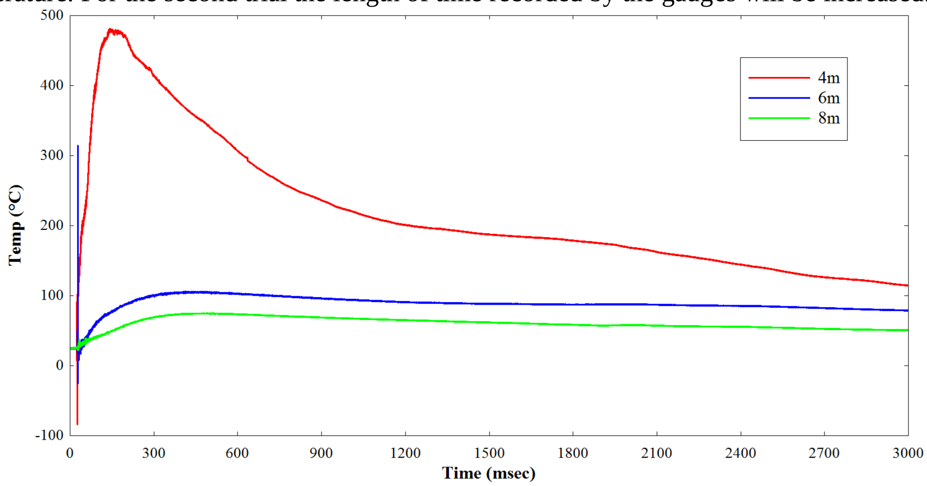

Figure 8. External Recorded Thermocouple Temperatures.

Fig.9 shows the internal recorded temperatures from the thermocouples placed on the rear face of the 2mm steel plates. The temperatures slowly rise to 36°C at 4m, 33.5°C at 6m and 32°C at 8m. Each of these temperatures was reached after 3 seconds. The curves of the plot suggest that the temperatures will not increase significantly more. It is also difficult to estimate the total rise and fall time and the actual peak temperatures reached. For the second trial, the gauges will be calibrated to read data for a longer period of time.

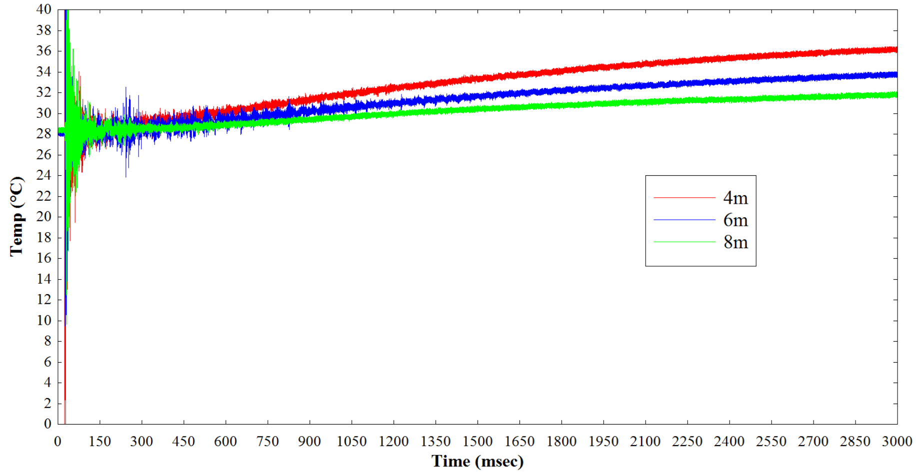

Figure 9. Thermocouple Temperatures on Back of Steel Plate.

Flux Gauges

Fig.10 shows the recorded flux. The peak flux recorded at 4m was 145 Watts/cm^2 at 32msec and the time to return to zero was approximately 500msec. The peak flux at 6m was 85 W/cm^2 at 55msec and the time to return to zero was approximately 450msec. The peak flux at 8m was approximately 30 W/cm^2 at 180msec and the time to return to zero was roughly 600msec. None of the recorded fluxes follow a triangular pulse shape similar to an applied impulse. The delay to the peak recorded flux increases with distance from the source. Comparing the flux with the recorded temperatures from the thermocouples, the flux gauges give a better representation of the thermal energy in the air during the event. This is due to the design of the flux gauge, where a cooling disc prevents the gauge itself from heating too much, allowing a better representation of the real atmosphere than the thermocouples which are left to heat and cool without intervention.

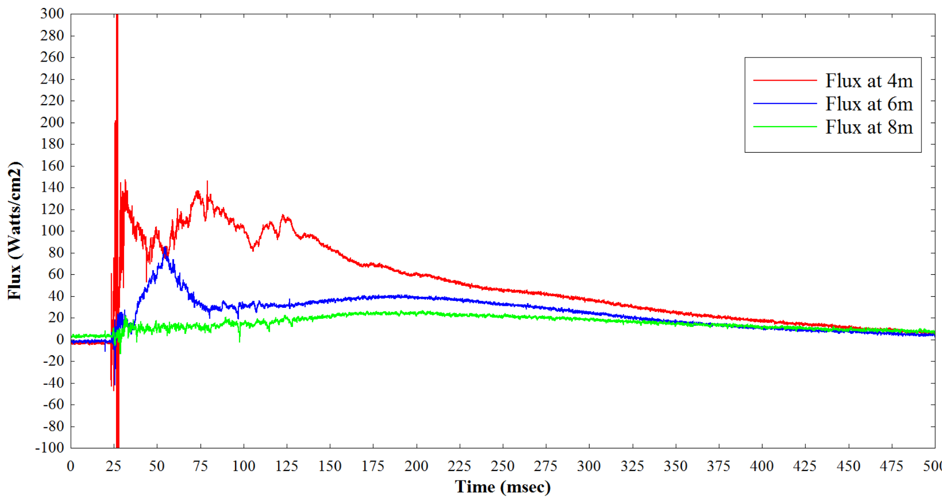

Figure 10. Recorded Flux.

Strain Gauges

The strain gauges were fixed to the back of the 2mm steel plates facing the blast at 4m, 6m and 8m **r**adial locations in order to record any elastic and plastic strains observed in the plates. As previously identified, a potential electrical disturbance at an early stage of the test (25msec) produced extreme readings that were not representative of real strains. Fig. 11 shows the recorded strains from the strain gauge (Rosette type) at the 4m location (largest deformations). The Rosette gauge has three separate individual gauges aligned in different directions; vertical (Red), horizontal (blue) and 45^o (green).

Due to the electrical disturbance the initial high and low strain values are difficult to determine. Using the Young's Modulus of 202x10^{3}N/mm^2 the strain values can be converted to equivalent stresses and the ultimate and yield strengths of the steel plates can be converted to equivalent strains to be compared to the plots. If the dynamic increase factors (DIF) are used (assuming yield is reached between 1 and 10msec) a factor of 1.6 can be applied to the yield stress and a factor of 1.05 can be applied to the ultimate tensile strength, giving 259.2N/mm^2 yield (1283µstrain) and 279.3N/mm^2 ultimate tensile strength (1383µstrain).

The vertical gauge on the plate at 4m recorded the strain settling at +700µstrain which has an equivalent stress of 141.4N/mm^2. This is lower than the yield strength of 259.2N/mm^2 (1283µstrain). The post-trial observations show the plate suffered permanent plastic deformations. This indicates that the strain in the plate would have exceeded 1283µstrain and then settled below the yield strength at 141.4N/mm^2.

The horizontal strain gauge did not show the same magnitude as the vertical, indicating that the stresses experienced were not radially isotropic. The horizontal strain settles at -315µstrain, which is equivalent to a stress of 63.63N/mm^2. The gauge at 45^o settled at -125µstrain indicating an equivalent stress of 25.25N/mm^2

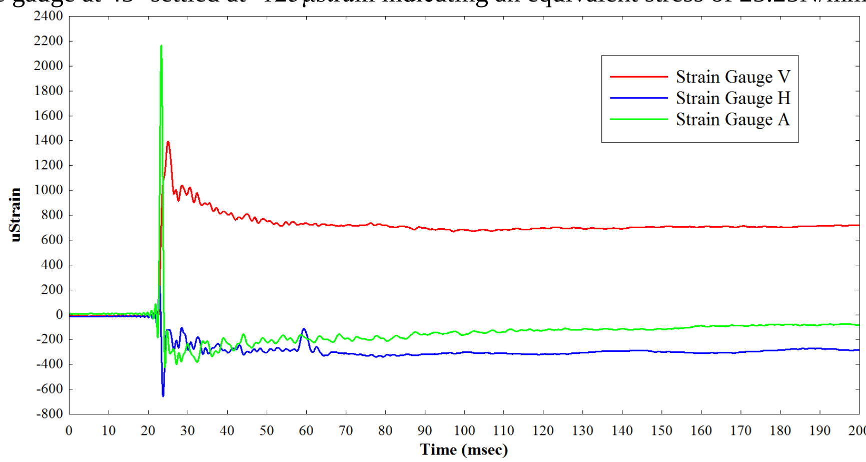

Figure 11. Strain Gauge Readings on Rear of Plate at 4m.

At the 6m radial location the steel plate experienced permanent deflections although not to the same magnitude as the plate at 4m. Fig.12 shows the strain gauge readings on the steel plate at 6m. The vertical strain gauge settled at -15µstrain, which is an equivalent stress of 3.0N/mm^2. The horizontal strain gauge settled at +200µstrain, (equivalent stress of 40.4N/mm^2) and the angled strain gauge settled at +30µstrain, (equivalent stress of 6.0N/mm^2) Although these stresses are low, the plot shows that higher stresses were experienced prior to the plates settling which caused the plate to deform beyond its plastic limit. The peak strain for the horizontal (blue) gauge can be ignored and the curve extrapolated back to give a maximum strain of approximately 1250µstrain.

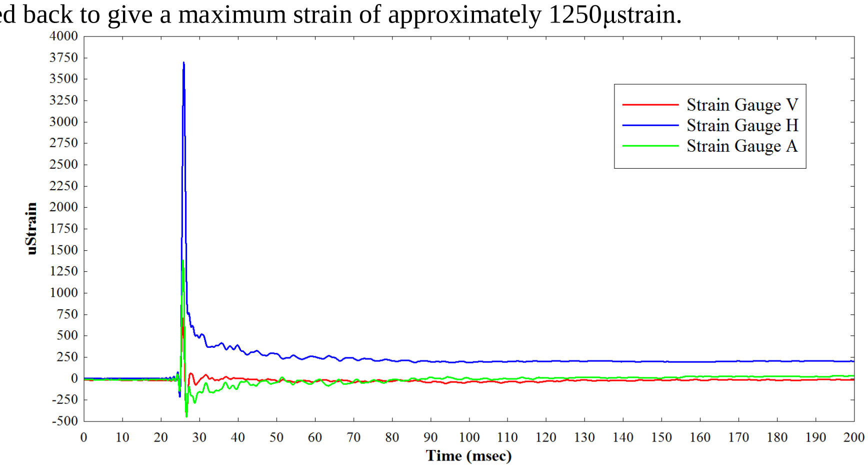

Figure 12. Strain Gauge Reading on Rear of Plate at 6m.

Due to a fault with the gauge data for the plate at 8m the full strain gauge plot is excluded from this report. However Fig. 13 shows the combined maximum strains experienced by each plate at 4m, 6m and 8m from the centre of the burst. The observed higher strains on the 8m plate are likely to be attributed to the gauge fault. The strain plots at

4m, 6m and 8m show oscillations, which may be due to the plates vibrating or an electrical disturbance with the gauges. The recorded oscillations were 10500Hz at 4m, 1000Hz at 6m and 700Hz at 8m; these are comparable to the natural frequency of a 150mm x 2mm thick square plate in its first mode of vibration of 814Hz.

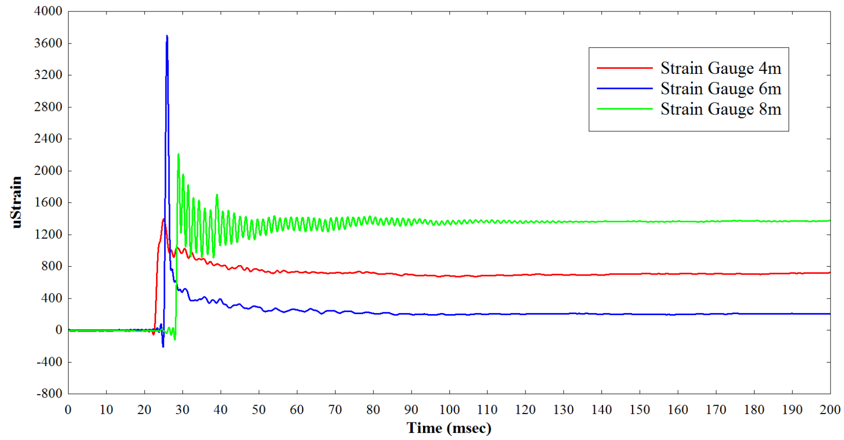

Figure 13. Max Strain Gauge Readings on Rear of Plates at 4m, 6m & 8m.

Deflected Shapes

Fig.14 shows the deflected shape of the plates at 4m and 6m recorded with a Vernier calliper. Fig.15 is a photo of the deformed plate at 4m. The maximum deflection recorded at 4m was 11mm, and at 6m was 6mm. The separate lines for each plate refer to the deflection profile in the X (horizontal) and Y (vertical) directions across the plate. (Note: A polynomial fit has been used to smooth the profile). The deformations of the plate at 8m were not measured as the Vernier callipers were not sufficiently sensitive to register such small deformations. The deflection plots show that the plate at 4m does not deform evenly; this uneven deformation is visible by naked eye.

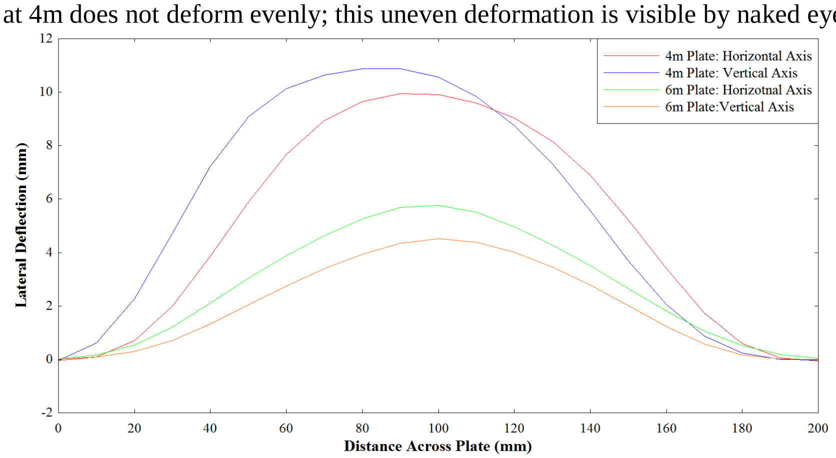

Figure 14. Lateral Deflection of Plates at 4m and 6m.

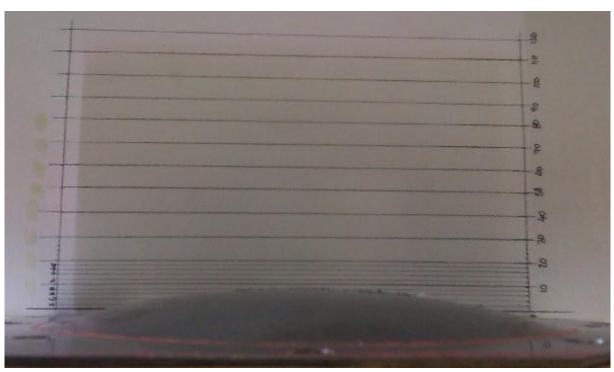

Figure 15. Photo of Deformations on Plate at 4m.

Discussion
During the explosive event the thermal load reached the plates after the blast wave, hence the synergistic effect involving the degradation of the steel due to thermal load prior to arrival of the blast wave did not occur. The thermal load was also too low to have reduced the capacity of the plates alone. The 2mm steel plate experienced deformations and the recorded strains exceeded the equivalent yield values of the steel. However an unloaded full size structural element with thicker gauge and higher strength steel would not see such stresses and deformations; therefore it is likely that such an element would not have yielded in this trial. This conjecture can be endorsed by the zero damage observed on the structural boxes. Lighter, thinner gauge structures such as cladding panels are more likely to fail in such an environment.

At 4m from the burst centre a double pressure peak was recorded. The explanation for the double peak is yet to be discovered but it does shed more light on the complex environment within a fireball. The gauge data recorded during the trial has provided us with a better understanding of the environmental spectrum from within a conventional fireball. Using this information a full parametric study into the synergistic response of structures within a thermal fireball can start to be formed.

To observe how structures can be affected by the thermal load from an explosion the research project will investigate fireballs of varying sizes. The thermal load from larger explosions will have a more detrimental effect on structures compared with the arena trial. Due to practical constraints surrounding the size of explosions that can be tested the thermal loads from such events will be replicated by other means. In order to do so a bespoke thermal tile has been developed to simulate such events.

THERMAL TILES

The simulation of thermal fireballs of explosive events has been well documented over recent decades. The ideal simulation profile of a large yield fireball is a steep flux increase followed by a slower parabolic decay; this flux profile would be applied over a full structural element. Previous simulation devices fall into two categories; large scale thermal simulators which produce lower accuracy rectangular pulse shapes and small scale simulators which can produce very accurate thermal profiles. Large scale simulators such as aluminium oxide jets can be used on full scale structural elements but issues such as thermal products, smoke, ventilation etc. have shown that combining the thermal simulator with a blast load is problematic. Small scale simulators such as solar lamps and Xenon heat flash lamps can only be used on small samples and are therefore more effective for investigating material responses as opposed to structural responses [1].

A new thermal tile is being developed that when ignited produces an extremely high thermal flux over a very short period of time. The tiles are made of a compound of titanium and boron and will be cast in a wax medium which holds the combustibles together until ignition. Due to the volatility of the tiles they need to be produced and tested in highly stable conditions. It is the intention to perform a trial which involves mixing the compound, forming the tile and igniting it using Nichrome wire. If this is successful then a series of experiments will be undertaken in order to benchmark the thermal tiles to assess their suitability to reproduce the expected thermal fluxes across a fireball from a large yield explosive event. The experiments will also be used to evaluate the tiles' suitability to be used within the large blast tunnel. The thermal tiles are based on a previous series of trials named the "Hi-Therm Simulator". These trials used the same Titanium-Boron compound but with different forming materials.

Previous Thermal Tile Research (Design Construct and Test of the Hi-Therm Simulator) [3]
The Defence Special Weapons Agency (DSWA, US) have developed and tested thermal tiles. The intention of this testing programme was to demonstrate if the thermal tiles could work as a high thermal simulator and be successfully combined with a subsequent blast wave. The targeted peak flux to reach was 150cal/cm^2/sec (628W/cm^2/sec), and a thermal fluence between 50 and 450 cal/cm^2. It was also imperative that combustion products from the tiles would not detrimentally interact with the later blast wave.

The concept of the thermal tiles involves combining two metallic elements which when ignited produce a highly exothermic reaction with temperatures exceeding 3000^{o}K. Unlike other thermal simulators there is no requirement for oxygen to enable the two metals to react. To fabricate the tiles the metallic elements are combined in powder form, acetone is then added to the dry powder to form slurry which is poured into 12" x 12" aluminium trays. A palladium cladded aluminium wire embedded within the tile is ignited and produces localised temperatures of approximately 2665^{o}K. This high temperature then initiates the Boron/Titanium reaction. Fig.16 is a diagram of the thermal tile.

Several series of tests were conducted by the DSWA. It was observed that when the trials were initially undertaken using small tiles a reasonable emittance (155Cal/cm2/sec) was recorded and there was little observable particulate ejecta. However, when larger trials were undertaken the recorded fluxes were less (40cal/cm^2/sec) due to increased products obscuring the radiation. It was also noted that there was a rapid increase in the recorded flux when the particulate fireball impacted against the gauges. This lends itself to the reasoning that the increase in flux was produced by conduction and convection through the particulates, as opposed to the ideal process of radiation. The full scale series of tests did not meet the requirements that had been set out and therefore left the opportunity for further development and testing. An outcome of the trials was the recommendation to use a higher density (low porosity) mixture and eliminate the volatile constituents.

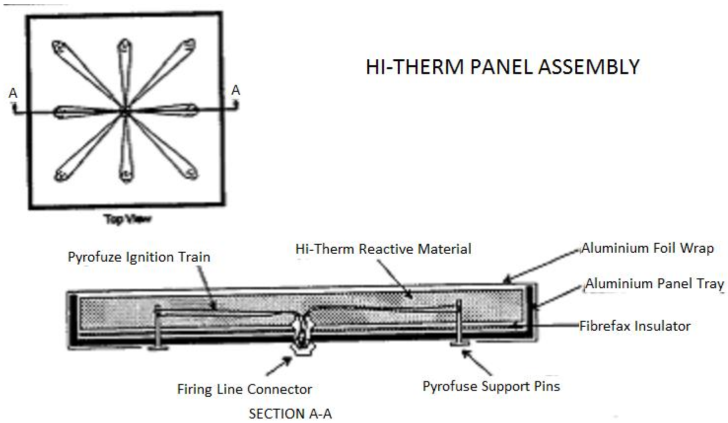

Figure 16. Previous Thermal Tile Configuration.

CONCLUSIONS AND RECOMMENDATIONS

This report describes a novel approach to recording information within a fireball. The temperatures, fluxes and pressures recorded from within the fireball help to form an understanding of the full environmental spectrum across a fireball, including phenomena such as the recorded double pressure peak at 4m.

The synergistic pattern with the highest potential damage criteria is for a structure to be subject to a high thermal load which decays the properties of the structure so that when a later blast wave arrives there is considerably more damage than would occur in the absence of a thermal load. In these arena trials the blast wave reaches the plates before the thermal load increases the plate's temperature so the worst case synergistic response does not occur. However, the external and internal thermocouples show the plates experience a temperature gradient from the thermal fireball. This gradient would induce stresses from the thermal expansion of the external face.

The temperatures, fluxes and pressures recorded in the trials will be used in correlation with data from the thermal tile experimentation and computational analysis on coupled (thermal and blast) structural elements to investigate the full potential synergistic response of structures subject to larger yield explosives. The thermal tiles are scheduled for testing during summer 2013, weather permitting. This paper has set the ground for these sets and future papers will document the results from the trials.

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