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RECENT DEVELOPMENT AND RESEARCH AT THE UNIVERSITY OF SHEFFIELD BLAST LAB IN BUXTON, UK

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ABSTRACT

The Blast and Impact Dynamics Lab in Buxton, UK has recently undergone a significant refurbishment due to investment by the University of Sheffield and funding from the Engineering & Physical Sciences Research Council (EPSRC) through a Strategic Equipment Grant. This has complimented development in measurement techniques funded through standard EPSRC grants and commercial blast testing undertaken by Blastech Ltd. a spin out company of the University of Sheffield.

This paper aims to discuss some of the recent developments that have been undertaken and introduce some of the technical work that this has enabled.

In summary, the recent developments include:

- Full site refurbishment
- Construction of an internal blast chamber rated to withstand 1 kg TNTeq
- State-of-the-art split Hopkinson pressure bar lab
- Improved diagnostic equipment
    - 2 × Shimadzu HPV-X2 ultra high speed cameras
    - 2 × Photron Fastcam SA-Z high speed cameras
    - Digital image correlation software
    - 4-channel 150kV Flash x-ray system
    - Telops Fast M1k MWIR thermal camera
    - High speed pyrometer
    - Mechanisms and Characterisation of Explosives apparatus (MaCE)
    - Underwater explosives testing facility
    - Modular confined blast (QSP) test chambers

INTRODUCTION

The Department of Civil and Structural Engineering at the University of Sheffield (UoS), UK, has operated a Blast and Impact research laboratory in Buxton UK for approximately 30 years. The lab is situated on the outskirts of Buxton, a town approximately 25 miles from the main University campus and is surrounded by the Peak District National Park. The consists of several concrete bunkers, first built around 1938 as an ammunition store for the Royal Air Force. In recent years, significant redevelopment of the site has been undertaken to provide state of the art research facilities in the field of blast and impact. This paper aims to highlight the current capabilities; areas of work and interest; and ideas for future collaboration.

BLAST TEST FACILITIES

This section details the various areas on site where tests are conducted and their capabilities.

Internal Blast Chamber

The highlight of the new facilities developments is the construction of a ~5×5×5 m blast chamber (Figure 1) with a capacity for testing of up to 1 kg TNT equivalent charges. This is due to be completed by November 2023. The chamber is designed with 9 portholes for cameras and data acquisition equipment to pass through and to allow for a wide range of experiments to take place using different configurations. There is a 12 m long firing range passing into the chamber to allow ballistic and impact studies to take place utilising the same instrumentation. The firing range is designed to operate with a range of fragment launchers up to 1500 m/s.

Figure 1: Render of the blast chamber, left ‘summer’, right ‘winter’.

Alongside the chamber is an instrumentation lab (shown in Figure 2) to allow various cameras and data acquisition equipment to be set up on a semi-permanent basis. This also includes an optical bench to co-axially locate multiple high-speed optical and thermal imaging cameras, so they share the same field of view. For example, this would allow for high-speed thermal and optical measurements of the same event to be taken and overlaid to probe the mechanisms within the explosive fireball.

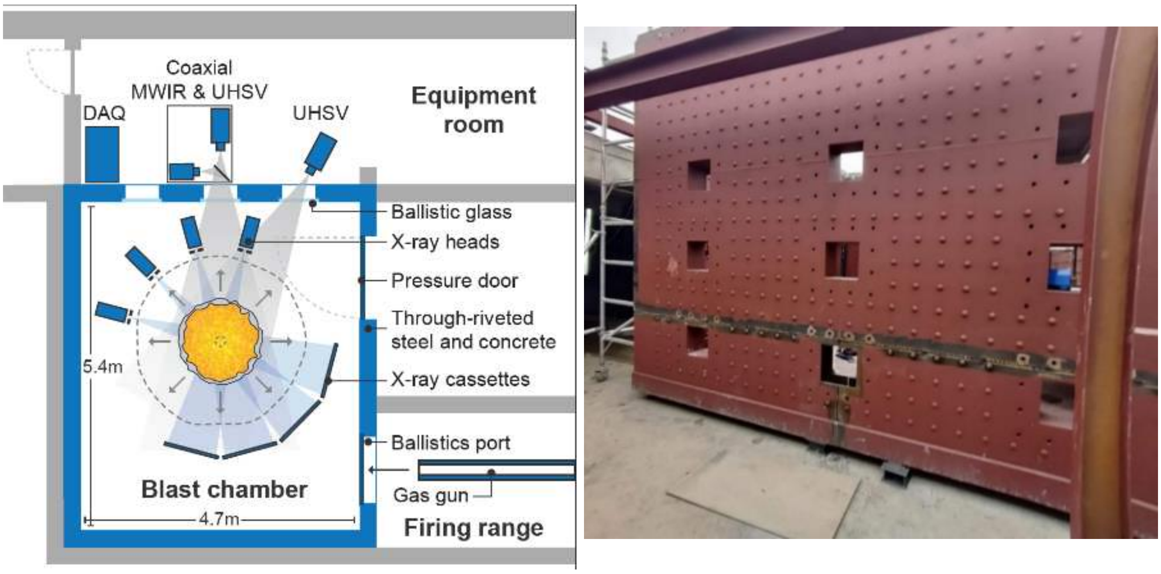

Figure 2: Left: Diagram of blast chamber and diagnostics available. Right: Construction of the blast chamber, showing the multiple apertures for optical diagnostics.

Far-Field Test Arenas

Several open arena areas are available for far-field blast testing. These include options for both reflected and incident pressure gauges with charge sizes up to approximately 1 kg TNT. Tests have been conducted with multiple different energetic materials such as PE4, PE8, PE10, PBXN compounds and ANFO [1][2].

An example of far-field testing is to characterise explosives at a range of stand-off distances. Tests are conducted between two gauged reflective walls to record the reflected pressure time histories. A diagrammatic representation of the test arena is included in Figure 4, which shows the arrangement with a charge centrally between the two instrumented walls. Figure 3 then shows the results from testing with 250 g hemispheres of ANFO showing the effect of detonation position in the 'intermediate' region (1 metre stand-off) is not present in the far-field region (2+ metre).

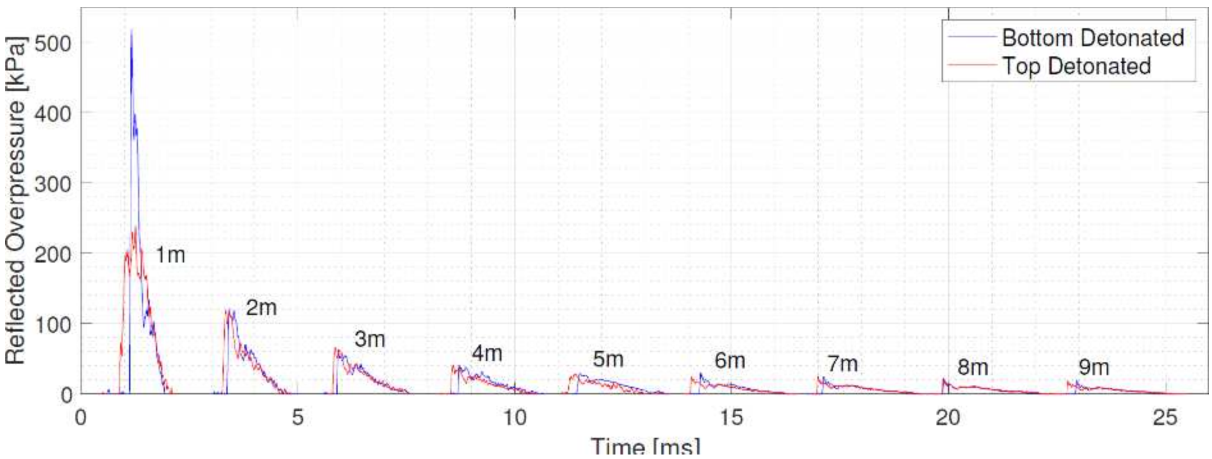

Figure 3: Pressure traces from ten far-field tests with 250 g ANFO hemispheres comparing top and bottom detonation [1].

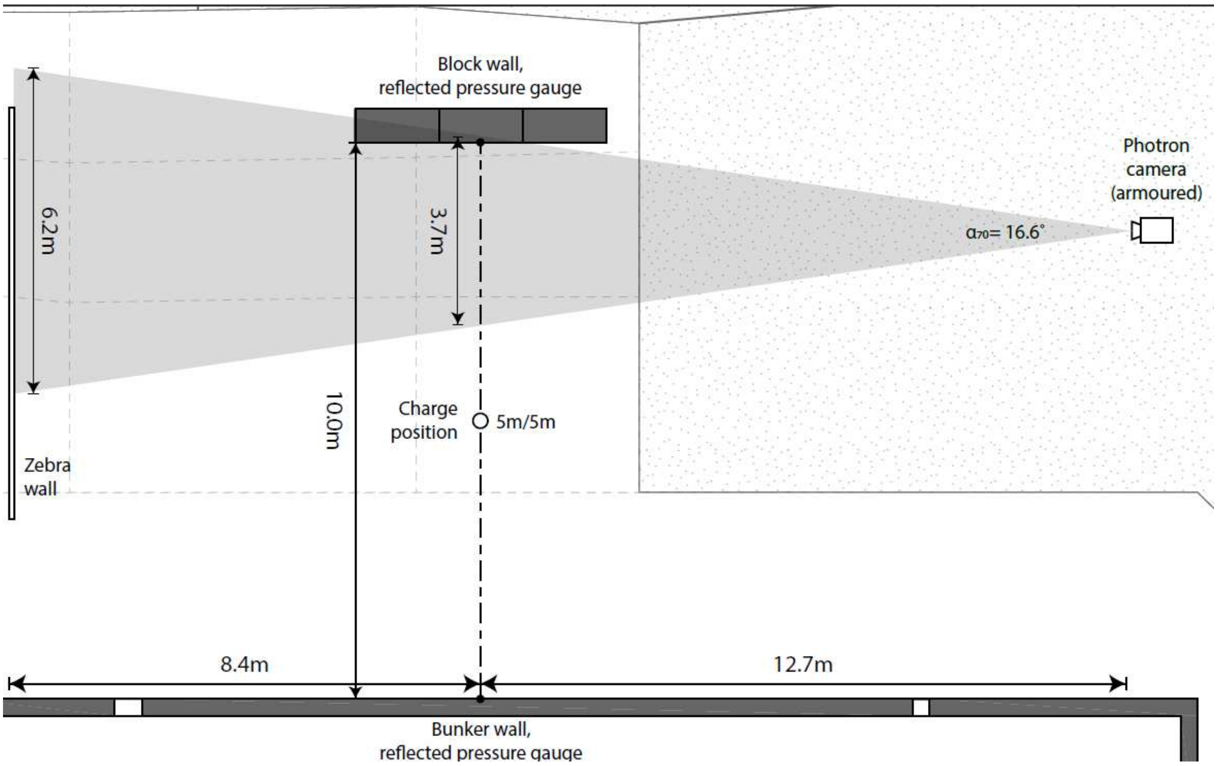

Figure 4: Plan of the far-field testing arrangement used for characterising explosives [2].

Confined blast chamber(s)

The confined blast facility comprises multiple cylindrical structural modules, each approximately 600 mm internal diameter and 1 m long with a 10 mm wall thickness and 30 mm thick end caps. The chambers are usable either individually or connected together to form an extended structure. The connections between the modules can be either fully open at the dimensions of the cross-section of the modules or choked down using an interface plate with a central hole to limit transmission of detonation products and shock waves between modules. The facility is fitted with pipework and monitoring equipment to allow the atmosphere inside the chambers to be controlled to investigate the effects of different amounts of oxygen (or other gases) on the pressure generated by the explosive.

The dimensions of the modules were designed to be suitable for the testing of 50 g PE4 charges within a single chamber. Figure 5 shows a diagram of a single chamber in use with the nitrogen atmosphere equipment connected. Figure 6 shows an arrangement of the test facility with four modules connected together.

Between tests, the chamber is fully vented, and any identifiable fragments or residue are recovered, bagged and labelled for reference. The chambers are then swept/vacuumed to remove any dust/residue to maintain a consistent environment for test-to-test repeatability.

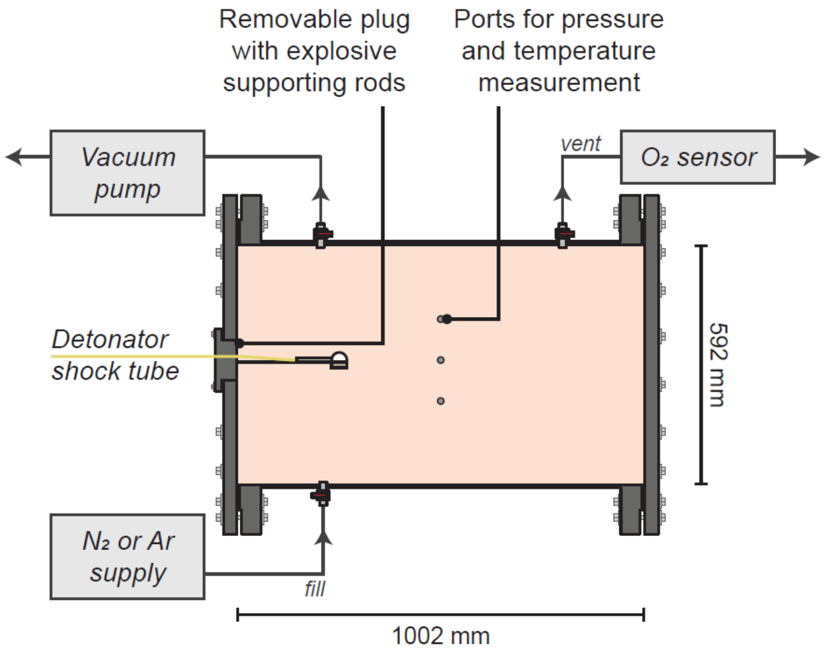

Figure 5: Confined blast module diagram showing the instrumentation, charge placement and equipment to control the internal atmosphere.

Figure 6: Four connected modules with a choke plate between chambers 1 and 2.

Pressure measurements are made in each module using Kulite HKM-375 or HEM-375 piezo-resistive pressure sensors with a natural frequency of >400 kHz. These gauges have been used successfully by the lab over many years for measuring reflected blast waves from free air detonations. Gauges with pressure ranges of 0-35 bar or 0-17 bar are typically used for 50 g PE4 charges.

Piezo-resistive pressure gauges have some sensitivity to temperature. Given the lack of certainty over how rapidly the gauges would heat up and the duration over which measurements would be required. Combined with the need to protect the gauges from damage due to impact of high velocity fragments it was decided in the original design of the facility to develop a thermal isolation mounting for the gauges. The principle of thermal isolation mounting is discussed by Walter [3] and involves the pressure sensor being, so far as is possible, isolated from direct contact with the detonation products by mounting it in a small air reservoir which is connected to the main blast chamber by a narrow tube. The system developed by the UoS follows this approach, using a 70 mm long M16 bolt as the isolation devices, with a 10 mm diameter hole drilled half the length of the bolt from the bolt head to act as the reservoir, and a 3 mm diameter hole drilled to the far end of the bolt to act as the connecting passage. The pressure gauge is then mounted in a threaded hole at the bolt head end and the bolt itself is screwed into a tapped hole in the confined blast module (Figure 7). It should therefore be noted that the discrete shocks recorded by the pressure gauge are not necessarily representative of the shock pressures at the inside wall of the module.

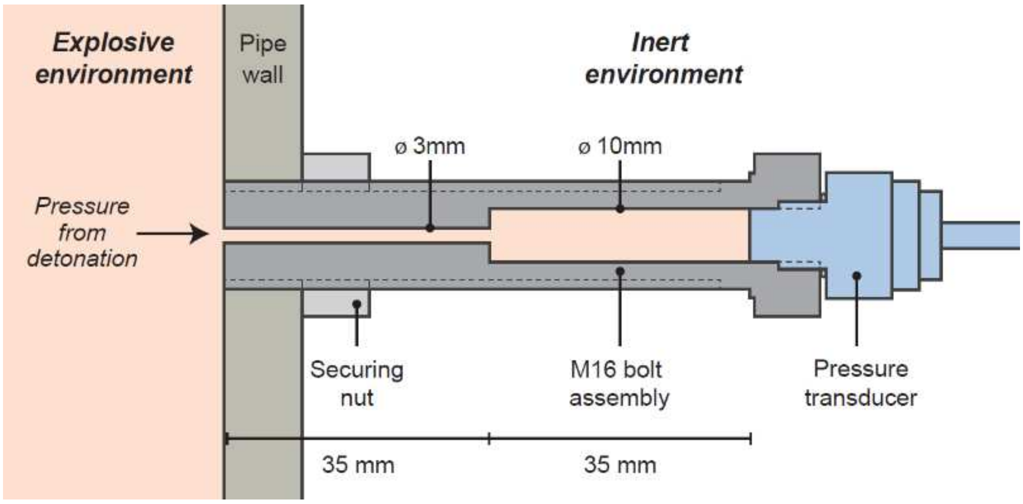

Figure 7: Thermal isolation mounting for pressure gauge

Underwater Explosive facility (UNDEX)

The UoS underwater explosives testing facility provides a unique capability in UK academia. The facility comprises a 2 m diameter test tank that is ~ 2 m deep with access from above to allow for materials to be added (see Figure 8 for a CAD diagram).

The capability enables informed advice to be provided regarding the performance of explosives underwater and the response of maritime structures, materials, equipment and systems to shock loading from underwater explosions. High explosive charges with masses of 10s of grams can be detonated either along the vertical axis of the chamber (for axisymmetric conditions), or close to targets mounted either in the chamber or in portholes the side wall of the tank.

The facility comprises fresh water with filtration options and the capability of altering the water chemistry if needed. The tank provides 6 test windows which are interchangeable depending on the requirements of test and instrumentation needs. It is supported by a range of instrumentation and pressure measurements with data acquisition rates up to 5 MHz as well windows for the high-speed and ultra-high-speed video cameras. Structural deformation testing with integration of digital image correlation is also possible.

Figure 8: CAD drawing of the UNDEX facility, showing the test tank and top access container above.

Figure 9 shows stills from high-speed imaging of a test highlighting the quality of videos that can be achieved with the optical diagnostics. Figure 10 shows example data traces from a similar test demonstrating the data that can be gathered with two independent gauge setups.

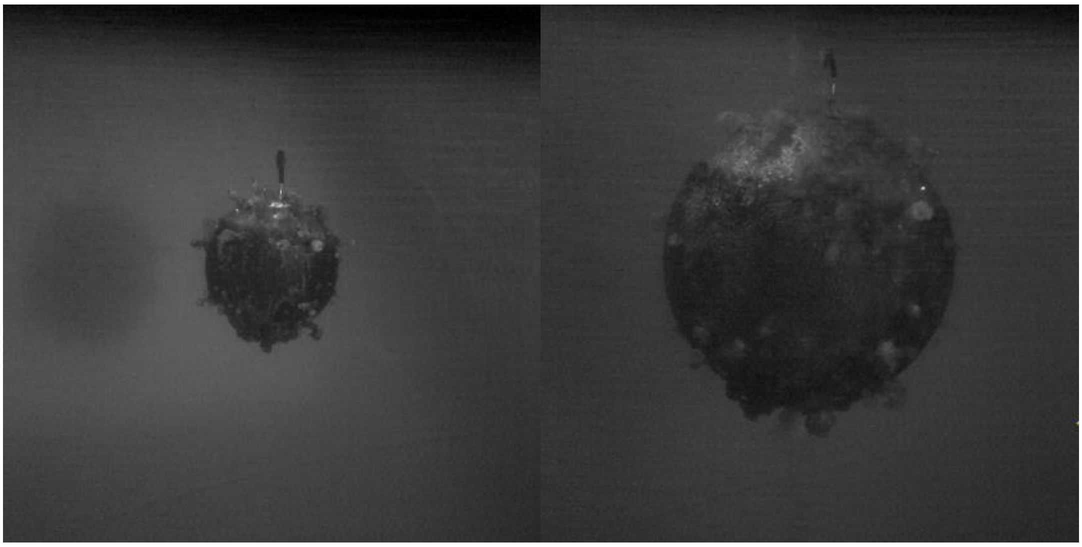

Figure 9: Stills from high-speed video showing the bubble formation at t=0.8ms and 5.7ms post detonation. (Recorded at 20,000 frame per second, with a total recording time of 1.5 seconds).

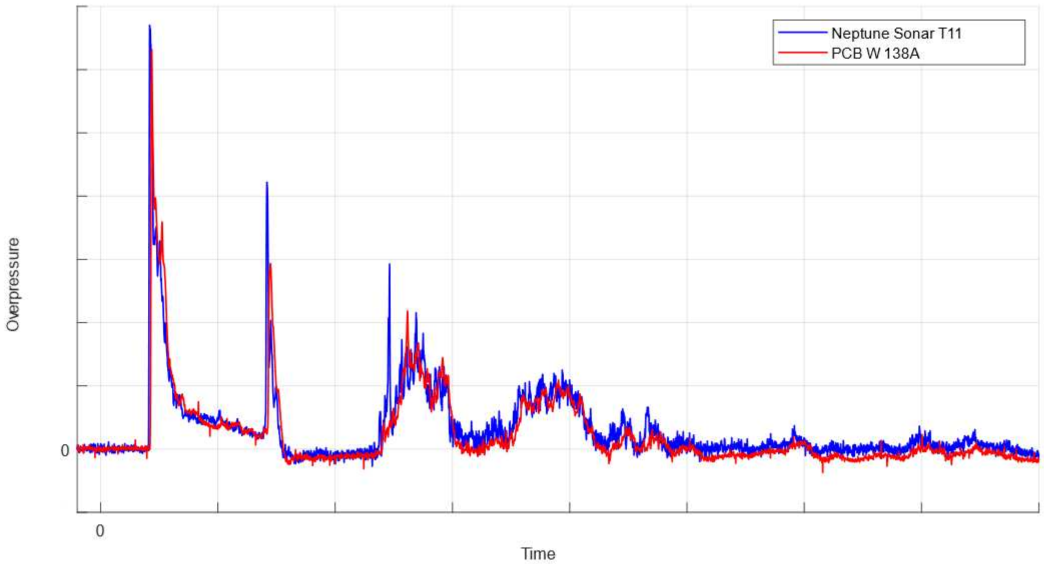

Figure 10: Example data from an UNDEX test showing the data consistency from two independent gauges. (Note: units removed to enable wider distribution).

OTHER FACILITIES

Split-Hopkinson Pressure Bar Lab

Numerical modelling of blast and impact events requires a robust understanding of material performance at high strain rates. The lab has a well-equipped Split-Hopkinson pressure bar (SHPB) facility (Figure 11) to perform material and mesostructural testing of specimens such as metals, soils, powders, explosives, foams, and additively manufactured lattices.

Repeatable testing is achieved using a pressure-controlled striker bar launcher, with a selection of pressure bar diameters and materials (steel, aluminium, polymeric) to suit the material under investigation. The SHPB pressure data (max acquisition speed 5 MHz) can also be supplemented with high-speed video (see below) to observe failure mechanisms or enable DIC measurements.

Non-standard testing of cohesionless/pressure-dependent materials can also be performed under fully confined or partially confined (Figure 12) conditions using specialist methods developed in house. This includes measurements of the radial stresses using strain gauges and/or pressure transducers and, optionally, the recovery of granular materials for post-test analysis.

Figure 11: Photo of the Hopkinson Pressure Bar lab with the striker mechanism on the left hand side.

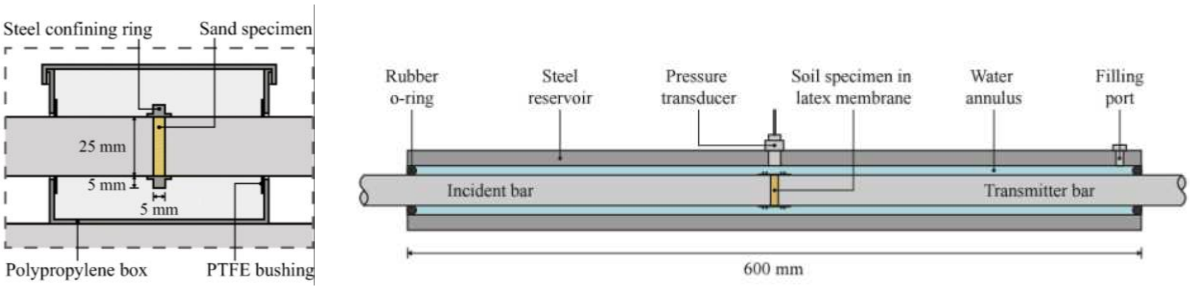

Figure 12: Methods for testing cohesionless or pressure-dependent materials such as soils a) full confinement in an instrumented steel ring [4], b) partial confinement using a fluid reservoir [5]

HSV Digital Image Correlation

The high-speed Digital Image Correlation (DIC) facilities are built on the research and development of group members and collaborators in industry and academia. The facilities can make use of several DIC commercial codes such as the new Correlated Solutions Vic3D, or the Dantec Dynamics Istra4D. In all cases, custom configurations can be developed to track the deformation of the target which could be flat plates, individual material samples or whole structures. An example setup is shown diagrammatically in Figure 13. In the case of blast plate experiments, we use the displacement field (Figure 14) of the target to determine the velocity profile and calculate the specific impulse to infer the loading on the target plate. This technique has been validated against other measurement techniques such as our CoBL facility and blast pendulums at other institutions [7].

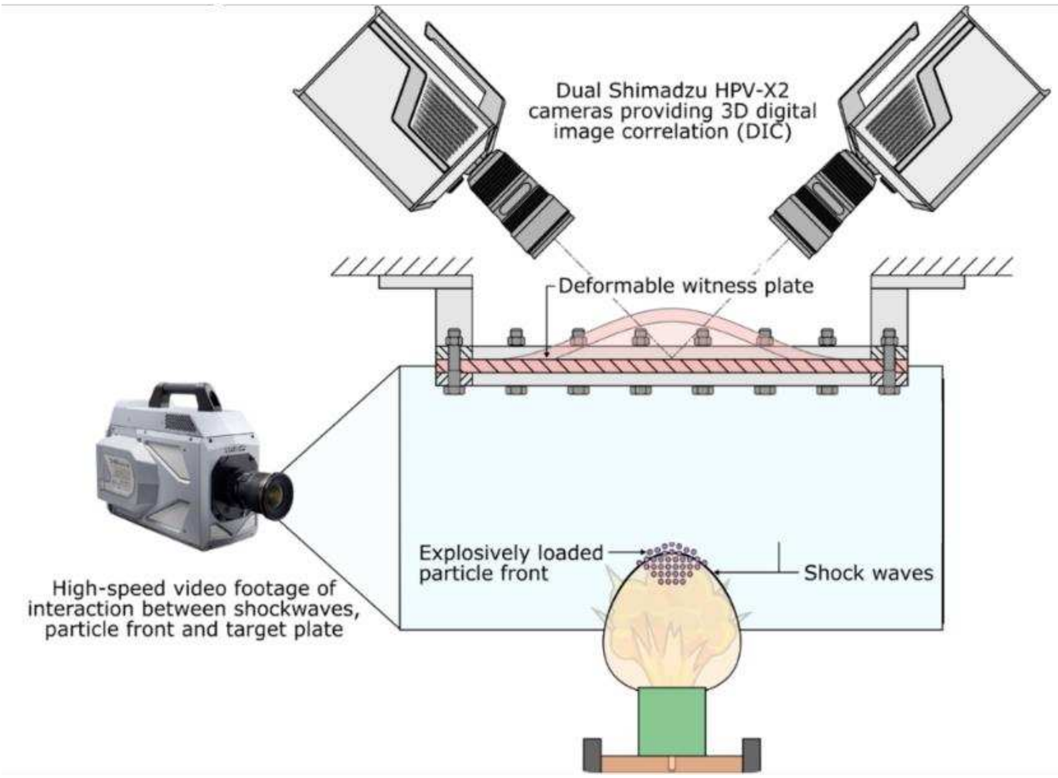

Figure 13: Schematic of DIC experimental setup for plate deflection test

To use this technique, special care needs to be paid to the speckle pattern size, quality and application technique. In each case an optimisation of the pattern size for the specific resolution and camera requirements needs to be undertaken.

The full-field data sets created can be linked to finite element models or used in virtual field applications to determine the material properties or unique field properties at extremely high frame rates without interfering with the deformation of the structure.

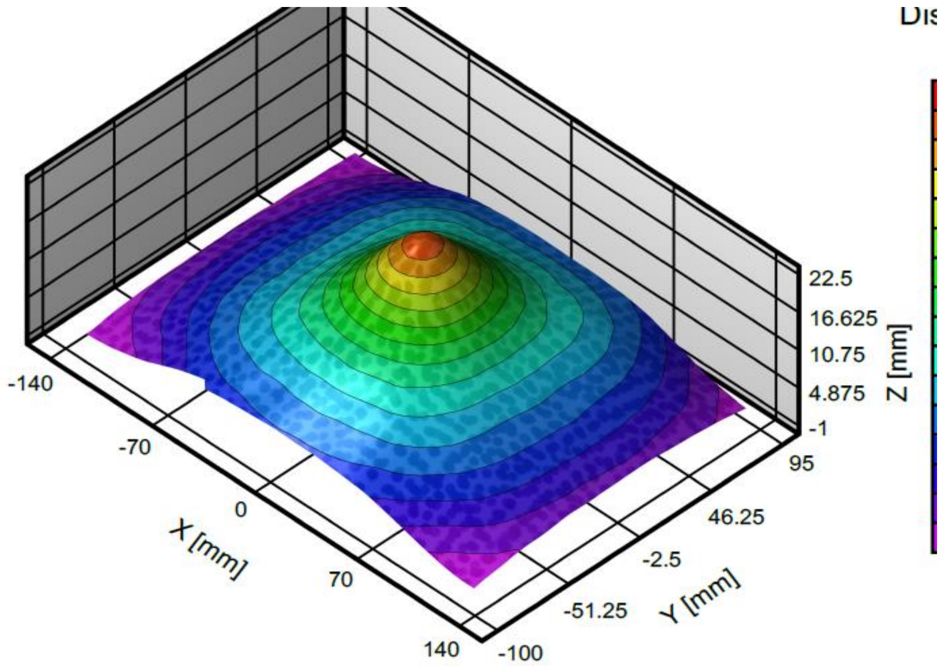

Figure 14: Example output from a DIC test showing the displacement of a target plate

DIC use for measurement of Ground Shock

Buried blasts can lead to ground shock loading of nearby structures in the soil and on the surface. Work has been conducted in the development of a new experimental technique for the quantification of this loading at a high resolution using high-speed DIC on a deformable plate in contact with the soil below an explosive charge. Recordings were made with a matching pair of Photron SA-Z HSV cameras. This testing made use of a 592 mm diameter steel pipe with a 3 mm aluminium base plate, clamped around the circumference. Testing has thus far been conducted using Leighton Buzzard sand at nominal 1.65 g/cm^3 bulk density and 5 % moisture content. Stand-off distance was varied between tests.

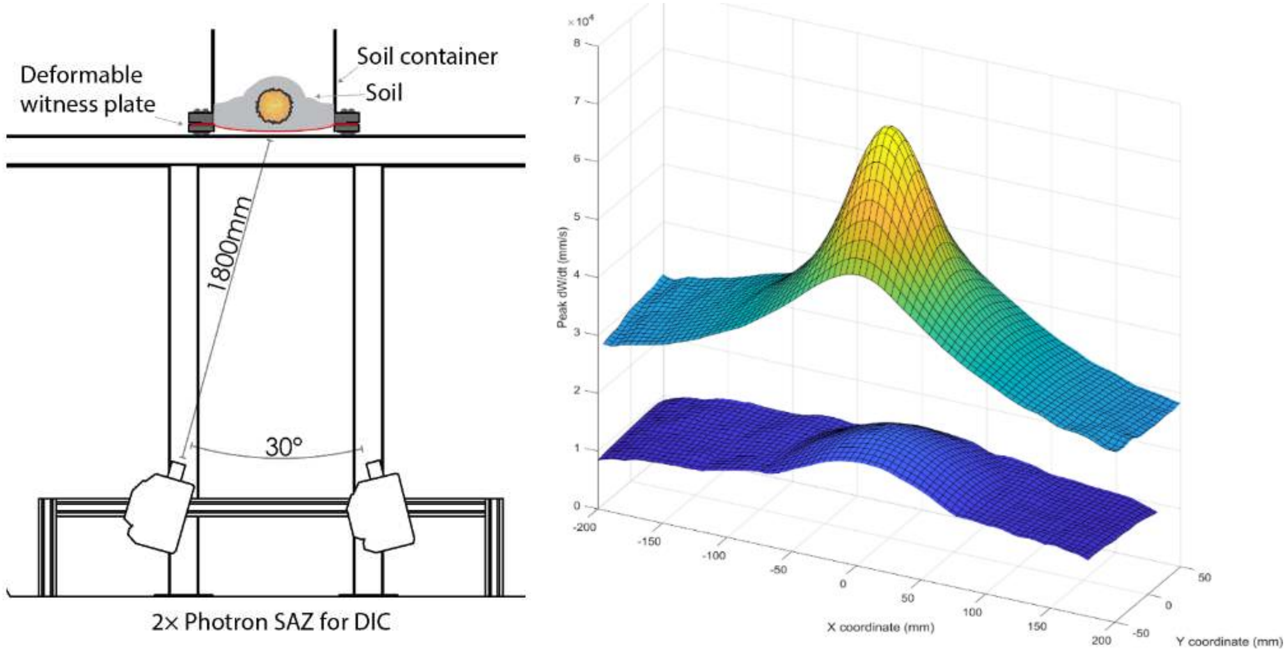

Figure 15: Left: ground shock testing apparatus with HSV cameras below the prepared soil 'bin'. Right: peak velocity surfaces for the area of data capture from two tests at different stand-off distances

Data was extracted from approximately 3500 locations across a major portion of the plate centre, with this recorded at a rate of 100,000 fps, allowing for both high spatial and temporal resolution of data capture. Plate displacement was directly recorded, with the deflection-time histories used to infer seismic velocity, plate velocity, acceleration and specific impulse. This allows for an enhanced knowledge of the ground shock loading behaviour impingent on a buried structure, improving upon discrete measurement techniques used in the past [6].

OPTICAL DIAGNOSTICS

High Speed Video (HSV)

The lab has access to a number of different high-speed and ultra-high-speed video cameras. There are three different sets of cameras in use in the lab with two of each available. They are: Kron Technologies Chronos 1.4, Photron FastCam SA-Z and Shimadzu Hypervision HPV-X2.

- The Chronos cameras are full colour battery operated cameras with high frame rates (1000's fps) typically used for wide angle 'arena' type videos to understand what is happening during blast events over a duration of 1-2 seconds.
- The Photron SA-Zs are the 'workhorse' camera providing a balance of speed (1000's to 100,000's fps), resolution and recording time.
- The Shimadzu HPV-X2s are ultra-high-speed framing cameras which allow for up to 10Mfps.

Alongside the various high-speed cameras, there are multiple options for flicker free, high intensity lighting to support blast testing including Luminys 30K Lablight and GS Vitec Multi-tiled MX lights.

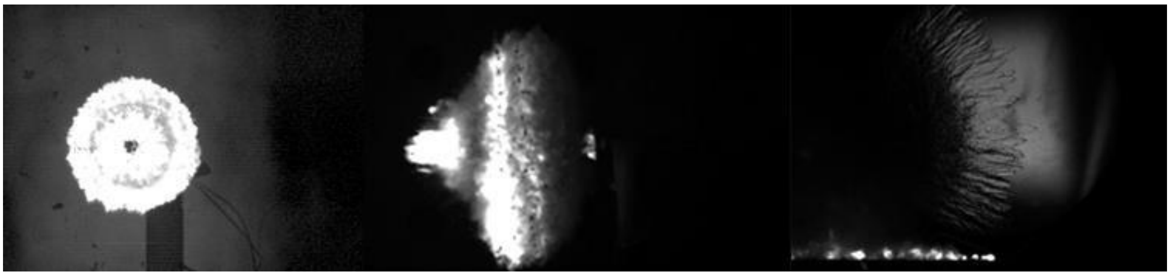

Figure 16: Images from high speed imaging using the Shimadzu HPV-X2 cameras showing: left) initiation of an electric detonator viewed end on showing the radial expansion of the detonator casing; middle) side view of a detonator showing the central weighting of the detonation products; and right) showing a wider field of view of the detonator fragments with a shadow graph of the fragments in motion, and bright spots where the fragments have struck the baseplate and ignited.

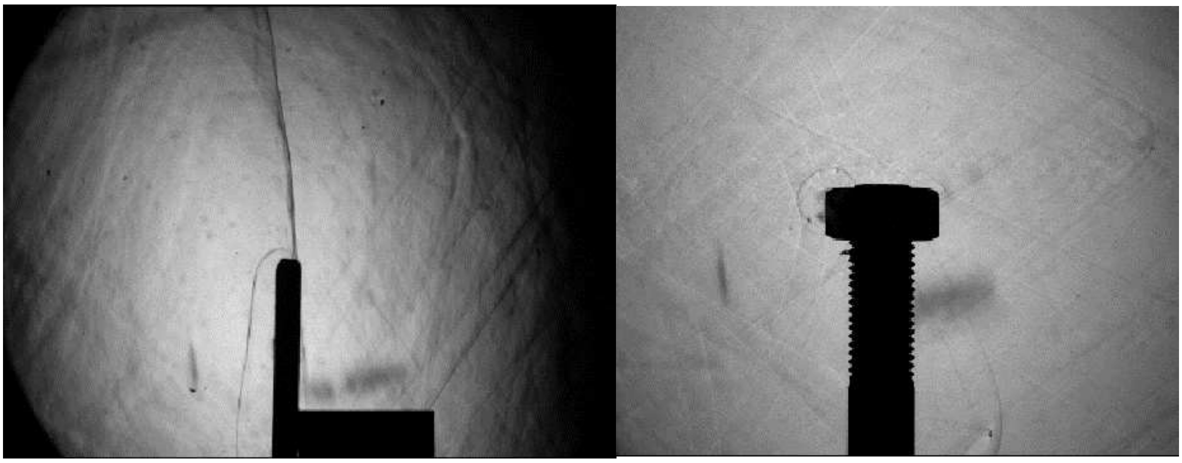

Figure 17: Still images from high speed imaging using a shadowgraph technique with the Photron showing: left) shockwave interaction with a 10mm steel plate (traveling left to right) with the reflected shockwave and clearing effect visible; and right) impact of a fragment of detonator casing with a bolt and the resulting shockwave radiating form the impact point (circular shocks radiating from the top left of the bolt head).

Pyrometer - Infrared Radiation Thermometer (IRT)

A high-speed IRT has been developed to measure the temperature of explosive detonation products with a response time of less than 1 µs. The IRT was designed and calibrated to operate in harsh environments, measuring temperatures in the 1200-2650 K range. Figure 18 shows diagrams of the IRT and its integration into a blast chamber [7].

Verification tests have been conducted deploying the IRT alongside pressure gauges in the confined blast chambers, Figure 19 shows the results of these comparisons. The left-hand plot in Figure 19 shows results from tests with the IRT and pressure gauge systems connected to the same data recorder with a unified time base. It shows that the IRT responds to the explosion approximately 200 µs before the pressure gauge, this is believed to be a physical effect with the IRT responding to the light emitted whereas the pressure gauge is responding to the shockwave which travels at a lower speed. Despite this temporal offset, it can be seen that the two measurement techniques both pick up the same transient effects The right-hand plot in Figure 19 shows the IRT recorded temperature compared to the temperature derived from the pressure reading via the ideal gas law over 0.5 seconds. This shows good agreement between the two measurement devices over the recording.

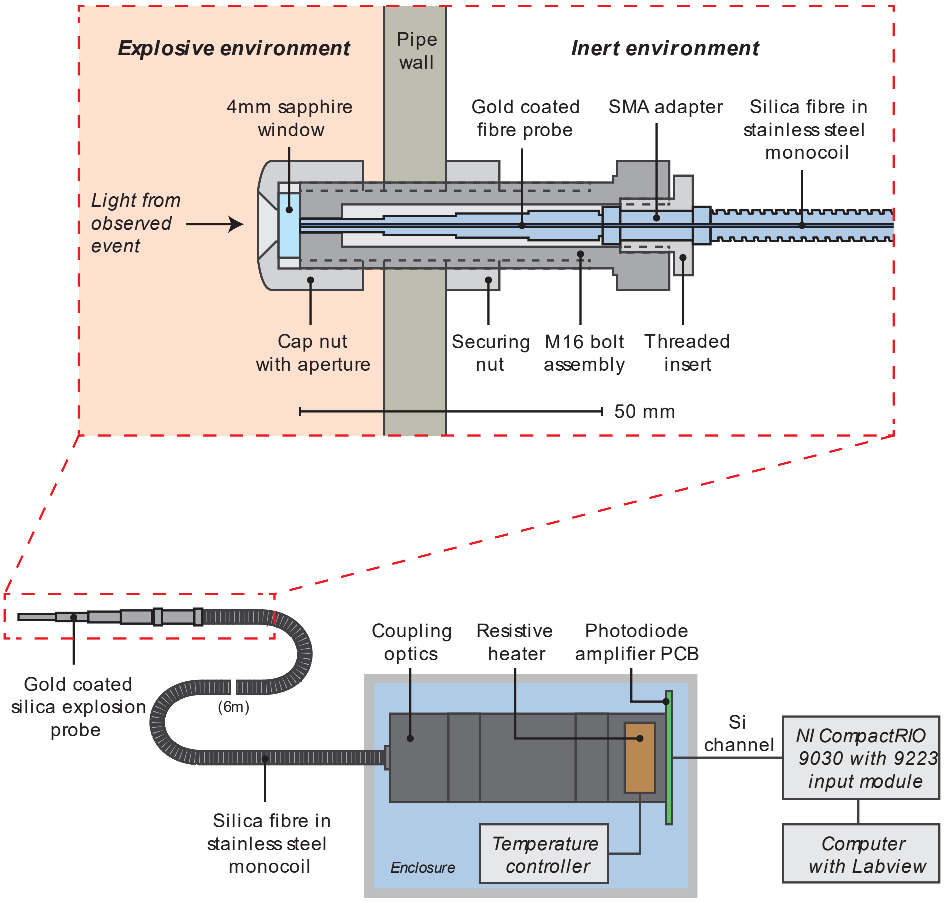

Figure 18: Diagrams of the high speed Infrared Radiation Thermometer (IRT) [7]

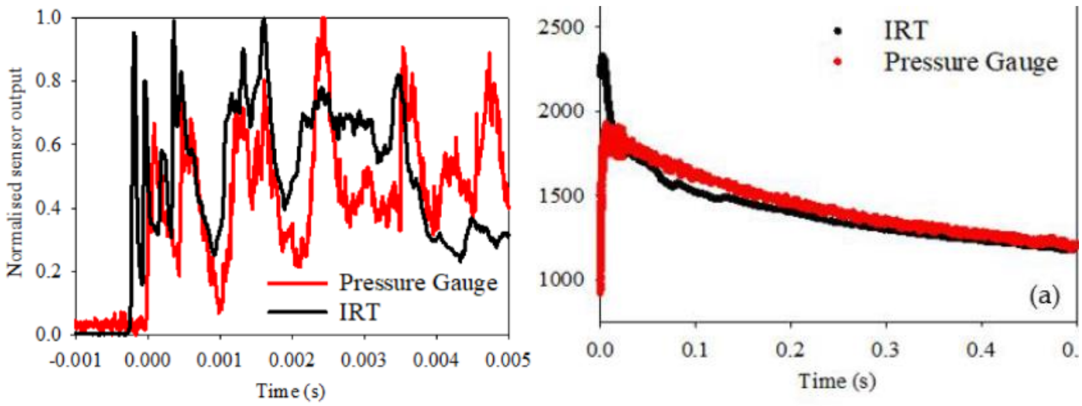

Figure 19: Comparison between IRT measured temperature and pressure gauge readings. Left showing the first 5microseconds and right showing the longer term comparison [7]

Instrumentation

CoBL – Characterisation of Blast Loading

The CoBL test rig was first developed in 2013 and has seen regular use since then [9][10][11][12][7][13][14]. The component parts are a stiff reaction frame constructed from steel and fibre reinforced concrete, into which 50 mm thick steel acceptor plates, at the underside of the concrete beam, are cast. Load cells are bolted between the underside of the acceptor plate and a 100 mm thick 1400 mm diameter mild steel target plate. The target plate has an arrangement of holes that accept 10 mm diameter 3 m long Hopkinson pressure bars. On top of the concrete beam, a Hopkinson pressure bar support frame is bolted such that bars are suspended and vertically aligned above soil bins. A schematic representation of the arrangement is included in Figure 20.

Each of the 17 bars used in the apparatus has two strain gauges attached to it in a balanced Wheatstone bridge configuration allowing the strain to be recorded by a high-speed USB oscilloscope.

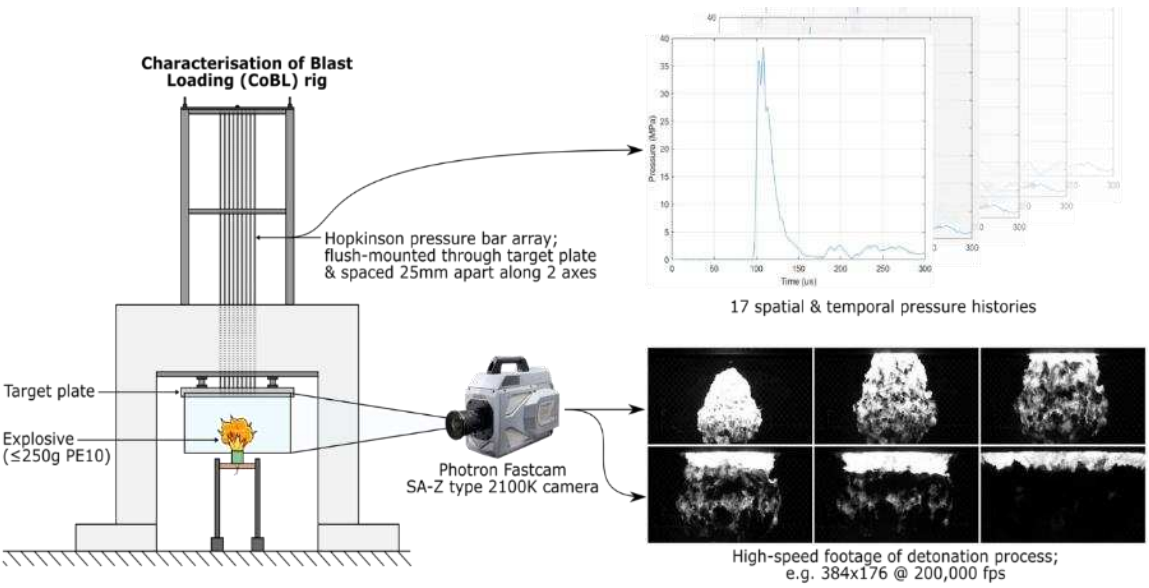

Figure 20: CoBL apparatus

MaCE – Mechanisms and Characterisation of Explosions

Building on the CoBL rig described above, the MaCE apparatus is the next generation instrumentation setup, utilising an increased number (37) of smaller (3mm) and more sensitive measurement bars (Figure 21). This apparatus allows for more accurate mapping of pressure time histories from blast events both spatially and temporally with a lower degree of signal dispersion due to the shock wave traveling along the bar from the event and the gauge point [15].

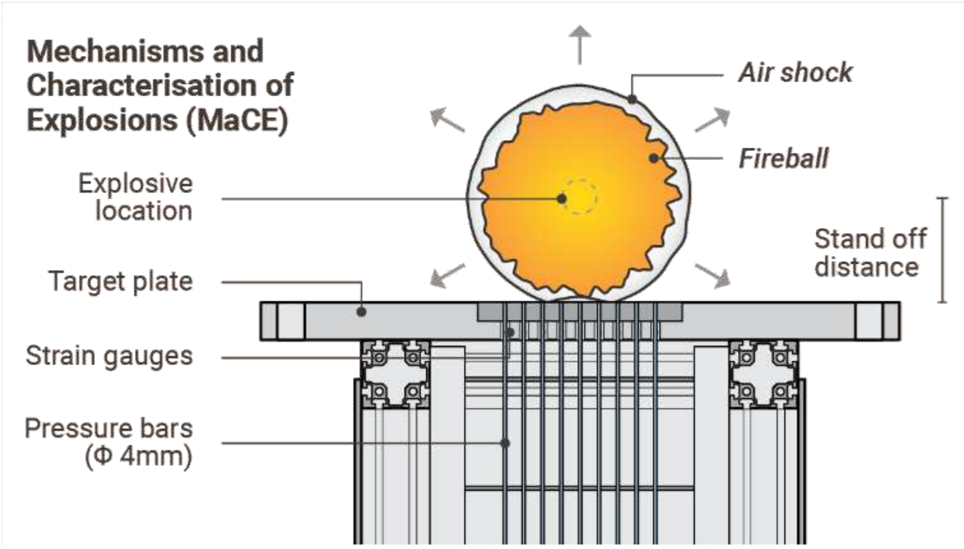

Figure 21: Diagrammatic representation of the MaCE rig

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