**Long duration blast loading of cylindrical**

**shell structures with variable fill level**

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**ABSTRACT**

This paper investigates the effect of long-duration blast loads on the structural response of aluminium cylindrical shell structures containing varying fluid levels. A detailed non-linear numerical model comprising remapped Lagrangian analysis examines localised plate buckling and deformation. The relative computational accuracy of an uncoupled numerical model developed in this paper is compared with experimental results obtained at one of the worlds’ most powerful air blast testing facilities. Evaluating structural response for blast loads with an extended dynamic pressure phase is exceptionally difficult using only Eulerian controlled CFD methods; due to domain constraints incorporating restrictive cell sizes engulfing the target structure before remapping. The further complexity of shock transmission through a structure damped by an internal fluid is examined experimentally. Fibre optic controlled instrumentation and high speed photography provide a vital insight towards coupled flow-field behaviour of the shell structure. Surface mounted pressure gauges on the cylindrical wall accurately record the pressure time history throughout the passage of the shock wave. This paper highlights the key influence on blast response due to varying internal fluid levels and the relative importance pertaining to a conservative design solution for varying operational states. Numerical modelling in this paper demonstrates the robust accuracy achievable for a remapped Lagrangian solution. The routine analytical assumption of uniform drag forces acting on the structural body was shown to be both misleading and inaccurate by comparison. This research will be of direct interest to both practitioners and researchers considering high power explosive blasts from sources such as hydrocarbon vapour cloud ignition.

**Keywords:** cylindrical shell, blast resistance, long-duration, structural response, fluid fill

**1. Introduction**

Cylindrical shell structures are an important component of many industrial processes and can be found worldwide in a wide variety of sizes and support configurations. Irrespective of diameter, they are constructed from a series of rolled welded plates continuously joined on all edges. Each of these plates will be curved with a bend radius dependent upon the final vessel sizing. The local plate curvature of small cylindrical assemblies will be high by comparison with bulk containment vessels of diameters in excess of 100m. Structurally, larger bulk storage vessels can present a near square projected area to applied loads due to their comparative building size. Cylinders can be positioned on raised stanchions or with full base fixity to the bottom shell course predominantly designed to resist overturning wind forces. The latter being most common with the former prevalent for smaller diameters typically present in petrochemical processes.

Despite the relative delineation, reduced diameter structural sizes will still consist of many metres. Importantly, in-service cylinders will contain varying fluid fill levels ranging from empty or non-operational to near volume locked and operational. Besides in-service loading, the structures will in limited circumstances be designed to resist a degree of accidental loading. The source of these loads will range from impact, fragment penetration, collision and explosive shock or blast. Potential collapse behaviour and the degree of any plastic shell deformation resulting from imposed loads will vary due to the interaction of the structure with any internal fluids; as a function of shock transmission, hydrostatics, sloshing and dynamic damping effects. Structural resistance and response to blast is an important consideration from the perspective of disproportionate consequence, collateral effects, operational resilience and potential economic loss. Accidental or deliberate blast loading can severely damage any cylindrical shell causing not only isolated failure but a progressive sequence of events in surrounding high and low criticality structures. The loss of fluid fill through a resulting shell breach presents a particularly high hazard scenario; giving rise to uncontrolled spillage, vapour release, liquid ponding, fires and secondary explosions.

The particular source of explosive blast load considered in this paper is long-duration, with a positive phase duration, Ta greater than 100 milliseconds; by comparison with conventional TNT equivalent explosives at approximately 10-20 milliseconds. Using the established Kingery and Bulmash equations [1] for radial charge propagation, > 30 tonnes TNT equivalency is calculated as the approximate absolute minimum yield for the formation of a long-duration pulse. By example, long-duration blasts with wavelengths of hundreds of metres are typically characteristic of unconfined hydrocarbon or chemical detonations; pursuant to the initial flame front ignition. Dissimilarity with smaller conventional explosive yields highlights the comparatively large energy deposition or blast impulse. This in turn extenuates overmatching of structures causing a destructive quasi-static response exceeding the natural period of the structure. Importantly, this loading regime quickly becomes a destabilising condition [2, 3]. Prolonged air pressure acting locally normal to the shell surface will continually worsen structural response. This becoming a function of distance between the resultant shear centre coupled to the rotating line of compressive force. Destabilising load conditions are in the main by comparison, rare design cases for what may be termed standard building structures; e.g., machinery capable of active spatial movement.

The effects of blast loading on structural elements are a key consideration in the design of new facilities and the assessment of existing structures [4]. This has arguably, never been more critical given: (a) large scale explosions such as the 2005 Buncefield fuel depot, UK and Azote de France (the former estimated at approx. 250 tonnes TNT equivalence) both damaging buildings across a 2-4km radius [5], (b) 2013 ammonium nitrate storage depot detonation in the town of West, Texas, USA (estimated approx. 200 tonnes TNT equivalence) killing 14 inhabitants and critically damaging 150 buildings, (c) large scale military explosive detonations such as the 1981 ‘Mill Race’ trial [6] and, (d) climatic changes leading to theoretically low probability design accidents e.g. the Fukushima nuclear power plant failure, Japan. In all cases, the potential for severe loss of life and critical damage to infrastructure is considerable due to the power and magnitude of the blast. Importantly, this is not confined within the immediate proximity of the explosive source (e.g. characteristic of vapour cloud flame front propagation). Pritchard et al [5] noted that damage to structures subject to longer duration hydrocarbon detonations vary dependent upon range. At close in, near field distances (< 10m), the fireball loads in the regular region are typically unrepresentative of high explosive TNT equivalency. Far field effects tend to be stabilised in nature with the formation of a planar Mach region or stem; specifically considered in this paper.

Blast loading and its interaction with structures is a complex phenomenon even in the simplest of settings. Modelling the effect of air blast and coupled structural response is a non-trivial engineering task. The difficulty is magnified when considering long-duration blast due to considerable drag loads imparted during the dynamic pressure phase. Evaluation of structures for the effects of blast loading is both experimentally and analytically demanding [7, 8]. Due to the number of simplifying assumptions required or the lack of accurate input data, the potential for error is considerable if only computational methods are used. This includes both the source term and high-rate material behaviour. Conversely, experimental procedures are complex and quite often prohibitively expensive, requiring specialist (usually national) facilities and dedicated operational expertise. Further issues pertaining to scaling effects of structures including, density and mass additionally complicate any trial planning. To the practicing engineer and most academic investigators, the evaluation of structures for transient dynamic blast loads can appear unachievable; particularly long-duration effects. As a result, a substantial degree of pragmatic conservatism is usually adopted with heavily factored quasi-static equivalent loads and single degree of freedom constructs [9, 10].

Isolated blast trials achieve varying degrees of success largely dependent upon prior experience. These will ultimately only yield a single binary result or small parametric variation. The main body of research examining dynamic response of (empty) cylindrical shells focuses upon comparatively small explosive sources and purely elastic material behaviour; borne by the complexity of non-linear modelling and the absence of capable experimental test facilities i.e. shock tubes [11, 12]. A number of investigators have examined the transient dynamic response of curved plates from a purely theoretical perspective using progressive computational methods [13, 14]. However, only small explosive TNT equivalencies were considered, none long-duration in nature and importantly, they did not include any comparative experimental testing as calibration or benchmark [15, 16, 17]. Neuberger et al [18] confirmed the challenge and difficulty involved with conducting full-scale blast experiments both in terms of cost and technical feasibility.

The most prudent research blends experimental testing with numerical ratification which is the key methodology presented in this paper. Conducted in the Air Blast Tunnel (ABT) at MoD Shoeburyness, a UK national facility [19], research in this paper specifically examines the coupled response of cylindrical shells with varying internal fluid levels. Importantly, this paper further considers whether it is possible to accurately model long-duration effects on these shell structures using remapped Lagrangian methods. Results from high fidelity analyses are compared for agreement and accuracy with fibre optic controlled instrumentation and high speed Phantom video photography. The action of long-duration blast loading on structures is an under investigated field of research with considerable applicability and importance to asset owners and practitioners.

**2. Experimental Procedure**

Experimental trials discussed in this paper were constructed and analysed at the national ABT, MoD Shoeburyness, UK. The ABT forms one part of a number of linked explosive research facilities on a single operational site. Overall, investigators can examine yields ranging from very small, comparatively short-duration charges (< 0.01kg TNT equivalent) to long duration, large explosives with sustained dynamic pressure phases (characteristic of > 500,000kg or 500 tonnes TNT equivalent). Trials considering the smallest explosive quantities are generally conducted on an open-air arena while the demands of long-duration shock wave generation are reserved for the environmentally controlled surroundings of the ABT.

The focus of this paper was directed towards the performance of cylindrical shell structures with the ABT functioning at 100% maximum power. Geometrically, the ABT is approximately 200m in length comprising two primary test regions as a function of tunnel taper. At the midway point a 4.9m diameter removable section and suspended floor plate subjects target structures to a peak overpressure of 110kPa with positive phase duration of approximately 0.2 seconds. Towards the exhaust end, the ABT widens to a 10.2m diameter permitting the examination of larger structures with a peak overpressure of approximately 55kPa for the same duration, see Figure 1 - tunnel in perspective view with experimentation area shown centre picture. The explosive driver source produces a planar shock wave as the ABT gradually widens in cross section. Negligible wave curvature exists towards tunnel boundaries thus subjecting any structure to a near Mach Stem loading regime. At the 10.2m exhaust end of the ABT, a rarefaction wave eliminator is installed to control shock wave expansion effects; thus prevent any degrading pressure reduction [19]. It is theoretically possible to fire at +100% maximum power but safety constraints pertaining to the primary superstructure govern. For normal ABT operations, a near Friedlander type blast wave is generated given the governing form stated in Equation 1, [20]. The energy deposition or impulse transferred to any structure in the ABT is substantial in magnitude by comparison with traditional smaller scale TNT charges; characteristic of open-air arena based trials.

Eqn {1}

Where: *p* = pressure at time ‘t’

*p0 =* peak static overpressure

*k =* wave form decay parameter

*t0 =* arrival time

Experimental operations in the ABT and any instrumentation installed on test structures are controlled autonomously through fibre optic link; synchronised with the precise firing point of the driver charge in relation to internal atmospheric conditions. The latter ensures trial consistency pertaining to planned versus target blast pressure. ABT environmental monitoring in the narrow and large diameter tunnel sections include static, reflected and dynamic pressure histories on and around structures. In addition to any pressure gauge or structural instrumentation e.g. strain and acceleration, deformed responses are recorded using high speed video photography (running at 6000 to 10,000 frames per second). In post-trial analyses, it is subsequently possible to compare shock wave arrival and diffraction via video photography with time sequenced gauge data. The records can be curtailed and magnified at any point for ratification with numerical modelling.

**2.1 Trial Setup**

Cylindrical shell structures present particular difficulties when conducting blast trials. Firstly, a curved facing area is aerodynamically efficient thus reducing the initial response to the shock wave; as a result, high impulse detonations are required to solicit a measureable response (excluding contact charges). Secondly, curved surfaces present additional challenges pertaining to the attachment of instrumentation and wiring e.g. successful gauge bonding to a non-flat surface. Testing of full-scale shell structures subject to long-duration blast loading was only possible in an ABT facility. Careful pre-trial planning was required to determine the optimum shell geometry that would respond reasonably for multiple fluid fill states: i.e. present measureable damage without complete collapse/annihilation or conversely, fail to respond at all providing little or no comparative data ratification. Overall, the final size of the vessel was mandated to meet ABT ‘choking’ or flow stagnation concerns (set at approximately 33% utilization of the tunnel cross-section) to limit potential facility damage.

Despite the immense power of the ABT facility, full scale cylindrical shells constructed from steel plate proved to be largely undefeatable at geometries that could be readily installed after prefabrication. Marine grade AA5086-H111, high quality aluminium plate of 4mm thickness was selected for the shell plates coupled to a 50mm thick aluminium base plate comprehensively bolted to the reinforced ABT floor. The bottom shell course was fillet welded to the base plate around the full circumference with no intermittent break simulating full fixity restraint to wind loading effects. Individual plates in each shell course were joined by a full-depth single vee butt weld of 1.6mm thickness at the throat tapering to 22mm; MAG welded with gas shield using a zirconiated tungsten electrode. The single vee was mechanically cut and file cleaned before weld initiation at a maximum inter-pass temperature of 200°C. All welds were independently inspected and passed for quality. Samples of aluminium used in construction were independently tested for mechanical strength and summary properties are shown in Table 1 for reference. Aluminium alloy AA5086-H111 has been reliably used for dynamic and impact response of plates by Abdulhamid et al [21]. To remain consistent with prior research considering only empty vessels Clubley [22], the maximum size cylinder was set: 4m in height to the hemispherical crown lid tip and 1.4m in outside diameter. It was not possible to install a taller vessel in the large diameter section of the ABT due to residual overhead crane clearance. Figure 2 shows completed installation and general arrangement of the test structure in the 10.2m tunnel section, on the centreline – depicting limited overhead clearance.

Figure 2 highlights the bottom section of the vessel was covered in a thin 50x50mm square hatched overlaid yellow livery. This colour scheme was designed to aid measurement of plate deformation using high speed photography and by comparison with numerical models subsequently defined with a matching mesh density. The chosen cylinder size remained constant for three independently tested fluid fill states; empty, 50% full and 100% full – or volume locked. The liquid contained was potable water (ρ = 1000kg/m3) as opposed to hydrocarbon fuel to mitigate significant safety and environmental concerns. Any breach in the vessel walls following shock wave arrival would potentially scatter fuel over hundreds of metres; presenting a secondary risk. British standard valve fittings were used to secure and retain all fluid fill. Each vessel fill configuration was blast loaded individually and in isolation with no re-use of any fittings, instrumentation, materials or structural components. A full calibration and setup protocol of all gauges and wiring was conducted before each firing.

The flow field environment around each of the three cylindrical shells was monitored with a comprehensive array of pressure based instrumentation. Peak static overpressure was recorded with PIS1, PIS2 and PIS3 labelled gauges with dynamic pressure measured across the ABT height with PDS’ labelled gauges; confirming the driver generation of a planar wave or Mach stem effect. For reference, the position of environmental instrumentation surrounding each cylinder is shown in Figure 3a. The shock wave arrives at the target structure from the North side, with diffraction and clearing towards the South side. Dynamic pressure instrumentation (PDS1-T, M, B) set in a 4.2m vertical array are shown in Figure 3b; measurement stings are marked at positions top, middle and bottom. The exact pressure history coupled to the time variant structural response of the shell surfaces was recorded using flush mounted Endevco pressure gauges. A total of five were installed on each of the three vessels; denoted PIST1 to PIST5. Flush mounted pressure instrumentation and concealed wiring passing through trunking represented a significant cost for three trials; traditionally reserved for aeronautics based experiments. As a consequence, surface pressure monitoring was restricted to the centre points of shell quadrants. Figure 4 explains the relative orientation of gauges PIST1 to PIST5 to the shock wave.

Structural response of the aluminium was measured with an array of bonded strain gauge rosettes installed at a minimum 100mm height above the base plate fillet weld. Figures 5 and 6 indicate the position of each gauge in conjunction with a fast response accelerometer attached near mid-height. Rosettes measured strain in three axes on North, South, East and West faces. Denoted by labels SNV, SNA & SNH, representing strain in blast facing North side plates for 90 degrees vertical, 45 degrees angled and 0 degrees horizontal, each rosette was mirrored per face; where ‘N’ is replaced by the direction considered e.g. vertically, SSV, SEV or SWV. Figure 6 indicates the position of two additional photography targets set at a predefined distance. These were required to provide a visual calibration of known reference when calculating particle velocity as a function of pixel movement during video playback. The ABT explosive driver configuration was set to perform at maximum yield consistent with loading assumed during the pre-trial planning phase; 55kPa peak static overpressure, 8kPa dynamic pressure and positive phase duration of approximately 0.2 seconds. Figure 7 shows a direct comparison of free field pressure gauge PIS2 and dynamic pressure gauge PDS1B for all three test cylinders. The pressure history shows excellent agreement between three independent trials for a demanding maximum power setting. Consistency was demonstrated for both time of arrival and maximum overpressure.

Figure 8 compares the overpressure recorded at PIS1 to 3 for successive positions along the ABT length. A good agreement in records is apparent indicating a consistent planar wave with minor energy degradation as a function of expanding shock propagation. Pressure history data was recorded during the experimental trials at a very high sample rate and contained a degree of electrical noise despite a fibre optic link. In post-trial analyses, original records were filtered using a standard procedure comprising a fast Fourier transform with low pass smoothing algorithm operating across a minimum two hundred data point sweep. The total experimental trial cost to fabricate, install, instrument and blast test three cylindrical shells with varying fluid levels was approximately £300,000.

**3. Numerical Modelling**

Computational response of each cylindrical shell subject to long-duration blast was examined using LUSAS FEA, Civil and Structural Plus analysis suite [23]. A solid model was defined to match the dimensions of the aluminium vessel shown in Figures 5 and 6; with the assignment of a thick quadrilateral shell element QTS8 capable of transverse shear based on an isoparametric interpolation order. A QTS8 thick shell element represents a robust choice to model curved plates where transverse shear stresses are present based on a degenerating continuum assembly. Local mesh density in the LUSAS models was set at 50mm x 50mm to exactly match the yellow hatched livery bonded to the cylinder base course, shown in Figure 2. Geometric non-linearity was included using an Updated Lagrangian solution scheme, permitting the evaluation of complex local distortion with continually destabilizing load. Mechanical strain calculations formed in an Updated Lagrangian scheme were based on the combined second Piola-Kirchoff stress tensor and the Green-Lagrange strain tensor. Both tensors can calculate large deformations tending to rigid body motion states; suitable for particularly adverse loading regimes characteristic of long-duration shock waves. Aluminium alloy used in the experimental trials was defined in the model using a stress potential controlled, total strain hardening plastic model subject to a Von Mises yield criterion for a continuum formulation. Stress strain characteristics were set to match the material properties shown in Table 1 with a dynamic strain rate amplification factor of 1.1. Strain rate effects for explosive dynamic loading range between 101s-1 and 106s-1. Blast waves in air induce structural strain rates typically within the range of 101s-1 to 103s-1 with higher values appropriate to hypervelocity hydrodynamic impacts. Long duration blast loads presented in this paper induced strain rates in the region of 102s-1. In this performance envelope the aluminium alloy is predominantly strain rate insensitive [21]. Quasi-static strain rate amplifiers of between 1.0 and 1.1 are appropriate depending on conservatism. In the absence of experimental experience, analysts select a value of 1.0 [7]; however, it has been found by experience this value is overly conservative and 1.1 is more accurate for aluminium alloys [22]. Monolithic full fixity was applied at the shell to base plate connection; representing standard detailing for wind load resistance.

To model the temporal load response of the cylinder, results from each flush mounted pressure gauge (PIST 1 to PIST 5 shown in Figure 4) were accurately remapped to the finite element model using sequenced pressure-time load curves. Pressure histories from adjacent quadrant gauges were parsed and amalgamated using a tapering, quadratic surface field variation preventing any step change unrepresentative of the diffracted flow field. The use of recorded pressures from the shell surface negated the standard analytical approach to use an approximated or ‘best guess’ global drag force modified by a coefficient multiplier, CD. The effects of flow stagnation, clearing and diffraction were automatically included. Figures 9 to 11 show the pressure history for gauges PIST 1 (front face) to PIST 5 (rear face) pertaining to each of the three vessels and fill states. Figure 9 depicts a time separated arrival of the shock wave graduated from full reflected pressure to free field overpressure and below at the rear cylinder face. A general Friedlander decay profile is evident with increasing time. By contrast, Figures 10 and 11 highlight a strong oscillatory response as a function of material ringing and fluid damping; global structural behaviour now dominating local plate buckling effects. It was not possible to include dynamic fluid translation and sloshing in the numerical model. An adjustment for mass fluid damping and internal hydrostatic pressure effects on the shell surface were applied using a split method of shell density recalculation as a function of fill level; further coupled to internal hydrostatic forces acting normal to the local shell surface providing an efficient solution strategy overall. Computational damping used the Proportional Method or Rayleigh Damping construct; incorporating both viscous modal and hysteretic structural effects. An eigenvalue analysis of each experimental trial configuration with fluid modifier was conducted to determine the mass and stiffness adjustment parameters. Metallic structural damping was set at 1% by prior experience [22]. In general terms, first peak response due to blast is largely unaffected by damping, particularly long-duration where an overmatching wavelength induces a quasi-static response. Damping effects are evident beyond initial response.

Non-linear solution control was manually integrated in the time domain for implicit dynamics using a LUSAS Fast Solver [23] on eight parallel CPUs with 16GB RAM. Typical solution times were approximately 600 CPU hours. An implicit construct was defined in LUSAS by consideration of the shock wave loading speed and impact severity (explicit solutions typically reserved for high velocity projectile impact above Mach speed). Implicit solution regimes are computationally expensive due to matrix inversion at each time step but are importantly, numerically stable for difficult load cases. The Hilber-Hughes-Taylor integration scheme or alpha method was adopted, defined in Equation 2 as opposed to a Central Difference Method for explicit solutions. Hilber-Hughes-Taylor permitted energy dissipation and second order computational accuracy across extended time steps incorporating the Newmark approach.

Eqn {2}

Where: *V0* = initial velocity for the initial time step

*A0 =* initial acceleration for the initial time step

*V1 A1* = velocity and acceleration at the first time step

*=* integration time step change

= Hilber-Hughes-Taylor integration constant

Comparative CFD analyses examining conventional charge weights were conducted in the planning phase using respected three-dimensional hydrocode, Air3D; designed specifically for air blast and shock wave loading constructs [24]. The Air3D solution scheme utilizes an advection upstream splitting method in parallel with a MUSCL-Hancock integration of the Euler equations. Air3D models are capable of accurately evaluating the effects of blast wave diffraction, stagnation and clearing [25]. Figure 12 shows a fourteen square metre domain on plan, mirrored about the centreline with flow out boundaries. A 10kg TNT equivalent charge at 9m standoff was used as a source term with; density = 1600kg/m3 and detonation velocity = 6730 m/sec. Figure 13 shows the shock wave developing a free field overpressure of approximately 55kPa and reflected pressure on the front cylindrical plate of approximately 115kPa; these values analogous to the free field and reflected pressures shown in Figure 9. A comparison of Figures 9 and 13 illustrates the positive phase duration is approximately 30 times greater for the long-duration case under examination. The net impulse or energy, transferred to the cylindrical structure being commensurately much larger by comparison. The CFD domain size required to model a long-duration wave length places considerable restrictions on the minimum cell size, as a function of the total array that can be successfully evaluated in terms of computing resources. A substantially extended domain is required to permit the complete passage and exhaust of the shockwave past the structure. A wavelength of many hundreds of metres dictates a restrictive total domain size of kilometres. Notwithstanding a considerable vessel size (illustrated in Figures 2, 5 and 6), it was not possible to model long-duration blast effects using CFD as the structure would reside wholly within one fluid cell. Consequently, no net load or surface pressure distribution could be accurately determined and thus, remapped to the finite element model. This illustrates the core challenge of both uncoupled/coupled analyses and the value of the experimental data presented in this paper.

**4. Results and Discussion**

A comparison of reflected and static over pressure coupled with local response of the cylindrical shell is shown in Figures 14a, 14b and 14c. The effect of fluid fill can be seen with respect to internal hydrostatic propping, sloshing and shock transmission. Following initial peak response, reflected pressure recorded at gauge PIST 1 for an empty cylinder displays a steady decay of load versus response. By contrast, partially filled and fully filled configurations induce a oscillatory dynamic response with minimal signal damping in the early stages. Reflected pressure on the north face (blast facing) varies greatly when comparing an empty vessel with fully filled. Figure 14a shows the history for the latter oscillating around ambient pressure with a number of severe peaks occurring at late times. Maximum amplitude does not exceed peak reflected pressure for an empty configuration. Oscillation for PIST 1 is in contrast to loads developing at the rear (south face) of the cylinder measured by PIST 5. Figure 14c shows a fully filled configuration developing approximately double the pressure magnitude following initial diffraction of the blast wave. Negative pressure readings are shown for PIST 5 in Figure 14c, due to turbulent flow during clearing inducing small wake vortices linked to local plate flexure; combined with internal fluid movement and shock transmission. This effect was less noticeable for side on pressures measured by gauge PIST 3, depicted in Figure 14b. Importantly, detailed pressure records shown in Figure 14 indicate the challenging nature of a single degree of freedom (SDOF) construct when trying to model thin walled shell response. The resistance curve for partially and fully filled are not constant or descending bi-linear forms (by reference to an empty state) and remain intrinsically linked to local plate displacement in response to propping effects. Reflected pressure records indicate a similar first peak resistance followed by rapid divergence. Only in absolute terms can the magnitude of pressure be considered similar for side on and rear facing effects; less for the latter case.

Figures 15a and 15b show the calculated impulse for all three fill states; indicating the relative work done or energy transferred to the system. Figure 15a indicates despite differing pressure records, empty and partially filled cylinders accrue largely similar impulse. A fully filled configuration does not display a significant impulse initially followed by a gradual rise at a roughly constant offset to empty and partially full. Figure 15b shows early agreement towards impulse with divergence at later times. Despite large oscillatory peaks in rear face pressure shown in Figure 14c (for gauge PIST 5), Figure 15b confirms the actual energy transference was not comparable with an empty cylinder; displaying a substantial degree of plastic deformation leading to structural collapse. The absence of increased flow stagnation in the stiffer fully filled configuration compared to severe local plate deformation in the partly or empty vessels gives rise to the difference in impulse shown in Figure 15. A lower pressure for an increased duration on ductile plating was detrimental by comparison with higher pressure for a comparative shorter duration on a stiffer, shock dampened assembly. During firing, the rarefaction wave eliminator (RWE) was set active in the ABT, shown temporarily open in Figure 1 for access. Use of the RWE ensured minimal pressure reduction at the cylinder during the shock wave exhaust phase.

Figure 16 shows the failure deformation of an empty cylinder following blast wave loading. This is compared inset with two numerical models examining an identical structure but subject to differing load ethos. The deformed model marked ‘false’ illustrates the erroneous answer generated when the numerical model was configured to solve global dynamic pressure effects on a projected area with a drag coefficient commensurate to a curved cylinder (CD = 0.5). Global sway translation and local buckling at the base plate was observed in the model depicted by the concentrated contours. This mode of failure was incorrect by comparison with the experimental trial demonstrating the importance of physical measurements. Subsequent replacement of drag loading for remapped pressure records produced an accurate model deformation by comparison with experimental testing; centre and left inset images shown in Figure 16. Importantly, an erroneous or ‘false’ failure mode denoted in Figure 16 is representative of general understanding or, ‘current custom and practice’ for blast loads by which an accurate pressure history is not know *a priori* – particularly characteristic of long-duration problems.

Figures 17 and 18 illustrate numerical model behaviour for comparative partially and fully filled cylinders. Differing degrees of local plate deformation are shown ranging from no damage to incipient collapse and breach. Computational adjustments to account for fluid damping and internal hydrostatic pressure distribution produced accurate final state results, highlighted by comparison of inset imagery shown in Figure 17. Figure 18 highlights the potential problems pertaining to an under estimate of internal fill level for the same cylindrical structure. Importantly, Figure 18 confirms the accuracy of the modified numerical model for a long duration blast load with respect to adaptive structural parameters, principally mass through shell density modification and stiffness adjustments pertaining to internal hydrostatic forces. Aluminium strain readings are shown in Figures 19a and 19b. Both front (North) and rear (South) faces of the shell exceed yield strain for an empty configuration in the early stages with a rapid reduction following diffraction of the blast wave. Strain on the rear face continues plastically without any further recovery. Strain records for the front face subject to the highest reflected pressures show early oscillatory reversal symptomatic of complex local buckling and plate deformation. By comparison, partially filled and fully filled cylinders fail to reach yield and slowly return to a mild metallic ringing with increasing time. Figure 19b displays peak strain values across an extended time returning to ambient pressure; showing the comparative total strain energy of additional fill states to an at-rest position. Inset Figure 19b indicates peak deformation for a partially full cylinder when vertical strain rosette readings reach approximately 2000 microstrain. No breach or loss of structural integrity occurred in the vessel. Figure 20 shows the numerical model was unable to match the initially severe peak strain values measured in the experiments; however, the curve shape after 10 milliseconds remains well characterised by comparison for the remainder of the time, which was substantial. Overall, figures 16 to 18 emphasise thin walled cylindrical shells are increasingly sensitive to an accurate spatial and temporal pressure distribution as opposed to shock transmission transversely through the container; thus, potentially simplifying the computational modelling demand and complexity overall as demonstrated.

**5. Conclusions**

This paper investigated the non-linear response of cylindrical shells containing varying fluid levels using blended or hybrid, numerical and experimental methods. Aluminium shell structures were subject to a series of high power, long duration blast loads characteristic of major accidental or unplanned events e.g. hydrocarbon vapour detonation or large explosive yields. Experimental testing in the Air Blast Tunnel demonstrated the inherent complexity pertaining to the response of curved plates coupled intrinsically with a blast overpressure and internal hydrostatic force. Without detailed knowledge of the flow field from the experimental trial instrumentation, accuracy of the numerical models was initially limited based on an assumed response mechanism. Importantly, complex pressure histories recorded on the shell surface confirm the challenging nature of a potentially simplified SDOF construct towards modelling transient dynamic response. Accurate characterisation of a resistance function and the mechanism of failure in a pursuant SDOF calculation would be subject to considerable speculation without recourse to knowledge gained from experimentation, as shown in this paper.

Analyses formulated upon a global drag force (as a direct function of dynamic pressure) produced erroneous failure modes not supported by experimental observation. Subsequently revised analyses incorporating shell density adjustments and remapped pressure histories measured experimentally produced numerical models demonstrating excellent agreement with final damage states observed. This paper highlights the general difficulty of modelling long duration blast loads on structures. Due to CFD modelling constraints pertaining to cell size, the domain size required to negate spurious boundary perturbations and overall shock wavelength, it is not readily possible to resolve net loads on structures. This is further complicated when the shape geometry analysed is curved or presents a reflection angle of obliquity. Remapping CFD results directly to a Lagrangian based solution scheme is therefore limited or at worst, fundamentally flawed. Only through a ratified approach of blended experimentation and high fidelity structural analyses can the true effects of long duration blast loads be evaluated accurately for a defined class of structure. Importantly, this paper shows practitioners and researchers in this field that it is quite possible to derive a non-conservative outcome; however, using the findings discussed in this paper a robust methodology is now possible given a modified solution scheme. Overall, the final high fidelity numerical model presented for cylindrical vessels of varying fill state displays a high degree of comparable physical accuracy.

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