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Long duration blast loading of cylindrical shell structures with variable fill level

Simon K. Clubley*

Faculty of Engineering and the Environment, Infrastructure Research Group, University of Southampton, Highfield, Southampton SO17 1BJ, UK

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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.

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 100 m. 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.

* Tel.: +44 2380 592884.
E-mail address: S.K.Clubley@soton.ac.uk

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The particular source of explosive blast load considered in this paper is long-duration, with a positive phase duration, T_a greater than 100 ms; by comparison with conventional TNT equivalent explosives at approximately 10–20 ms. Using the established Kingery and Bulmash equations [1] for radial charge propagation, >30 t 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 t TNT equivalence) both damaging buildings across a 2–4 km radius [5], (b) 2013 ammonium nitrate storage depot detonation in the town of West, Texas, USA (estimated approx. 200 t 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 (<10 m), 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,

Table 1
Aluminium material properties.

Tensile test – BS EN ISO 6892-1 2009
Material: 5083H111 aluminium alloy

Sample no.	Gauge length	Thickness (mm)	Width (mm)	Area (mm^2)	0.2% Proof stress (MPa)	Max stress (MPa)	Elongation (%)
1	A5	4.00	20.00	80.00	163	302	30
2	A5	3.92	20.00	78.40	144	290	16
3	A5	4.00	20.00	80.00	139	293	24
4	A5	4.00	20.00	80.00	165	299	26
Mean	–	–	–	–	**153**	**296**	**24**

Fig. 1. Air blast tunnel – entire structure.