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Non-linear long duration blast loading of cylindrical shell structures

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ABSTRACT

This paper investigates the influence of long-duration blast loads on the structural response of aluminium cylindrical shell structures. Full scale coupled non-linear dynamics are examined experimentally at one of the worlds' most powerful air blast testing facilities. Evaluating structural response to blast loads of this magnitude is exceptionally difficult using only computational fluid dynamics; typically not achievable without incurring unmanageable solution domains. Clearing, diffraction and exhaust of a long-duration blast wave across any comparatively small structure imposes constraints leading to the use of approximated drag coefficients, designed primarily to expedite the calculation of net translational forces. In this research, detailed pressure histories measured experimentally on the surface of the cylindrical shell are used to accurately configure a computational analysis dispensing with the requirement to utilise approximated drag forces. When further combined with accurate material test data, fibre optic controlled strain gauge instrumentation and high-speed video photography, a full comparative model was possible. This paper shows that without exact knowledge of long-duration flow-field effects *a priori*, it is very difficult to reliably determine the mode of structural response and degree of blast resistance. Preliminary modelling predicted a global sway and localised plate buckling; however, subsequent experimental testing showed a crushing failure of the shell before any translational movement occurred. Results in this paper will be of direct interest to both practitioners and researchers considering the dynamic response of cylindrical shell structures subject to high power explosive blasts from sources such as hydrocarbon vapour cloud ignition.

1. Introduction

Cylindrical shell structures are found in many commercial and industrial settings. Dependent upon their application or use, they may be positioned singularly or in complex arrays of multiple assemblies. The most common occurrence is petrochemical or pharmaceutical. Operationally, the vessels may reside at the end of a long process and act as bulk storage or conversely form part of an in-line chemical engineering activity. Structurally the shells are supported on raised platforms or conversely fully fixed to a base plate. Blast robustness of cylindrical shells is an important consideration to prevent a catastrophic singular or progressive sequence of failure. The source of explosive ignition and shock propagation considered in this paper is unconfined vapour cloud detonation after the flame front. Blast loads of this type are extremely severe and by comparison with conventional explosive, long in time duration approaching 0.5 s, as opposed to 10–20 ms [1]. The energy deposition or impulse, in this time frame is considerable; in many cases, the duration of the blast load exceeds the natural mode of the structure and response becomes quasi-static and destabilising [2,3].

Blast loading to the exterior of a cylindrical shell is an accidental load case imposing statistically severe actions. The 2005 Buncefield vapour cloud explosion in the UK demonstrated the substantial cost of long duration blast damage to both surrounding commercial buildings and industrial equipment [4]. Steel frame and masonry buildings were demolished while shell structures or tanks, used for bulk storage collapsed causing further spillage, fires and secondary explosions. The degree of collapse or plastic deformation depended upon the internal fill depth and any proximity effects to shielding structures. In a number of cases the long duration blast swept away the exterior skin of the shell due to over matching. Structures surrounding the explosion were only designed for a combination of wind and snow load pressures. This is a reasonable and common occurrence given the direction of design codes.

The effects of long duration blast loading on cylindrical shell structures remains an important topic for investigation with little research other than qualitative post failure analysis [4,5] or simplified analytical methods in Baker et al. [6] and Kinney [7]. This is in part due to complexities in experimentation and analysis encapsulating coupled structural response within a long wavelength flow field [5,8]. It was noted by Pritchard and Roberts [5] that damage to structures subject to vapour cloud detonation varies dependent upon whether the range to the explosive centre is very short or at

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Fig. 1. Air blast tunnel – entire structure.

Fig. 2. General arrangement.

distance. Structures immediately adjacent to the detonation are subject to complex fireball loads unrepresentative of high explosive TNT equivalency; whereas, far field damage demonstrates more similarity due to 'shocking-up' of the blast front. Sources of long duration vapour cloud explosions and their potential mitigation were studied by Nettleton using helium and carbon dioxide curtains [9]. While successful in an experimental construct it remains difficult to deploy around all potentially affected structures, particularly when complex multi-stage detonations can occur as illustrated by Birk et al. [10] in the study of two step boiling liquid expanding vapour cloud explosions. This paper specifically considers far field effects on shell structures due to the formation of a near planar shock wave or Mach stem.

Early research examining the dynamic blast response of cylindrical shells and the constituent plates they comprise, focused upon comparatively small explosive sources and elastic behaviour. In many cases, the analytical construct was simplified due to common reasons, (i) resolution of non-linear dynamic response was a formidable task combined with hypothetical load conditions [11,12] and, (ii) experimental constraints dictated that scale models were required i.e. small shock tubes, in which subsequent application to full size structures was difficult [11]. In an attempt to overcome the analytical difficulty, Jiang and Olson [13] modelled the transient response of cylindrical shell structures using a curved finite strip formulation. Focus of the research was directed towards very short blast time durations, leading to impulsive dynamic response only. Transient response of similar cylindrical shells were examined in a theoretical study by Li and Jones [14] and Lellep and Torn [16] but for short clamped positions with perfectly plastic materials subject to a predetermined cubic yield criterion. Consistent with Jiang and Olson [13] and Pedron and Combescure [15], only small explosive blast loads were considered with the latter evaluating the response of an immersed shell structure.

A number of researchers have considered the localised dynamic response of circular and curved shell plates when subject to blast loading in isolation. The explosive detonation originating from both internal and external sources, ranging from military circumstances [17] to unplanned petrochemical process failures [18]. Research remained theoretical in the main with a limited array of miniaturised experiments and hybrid formats [19] in accordance with the Hopkinson scaling law. Neuberger et al. [17] reiterated the difficulties involved with conducting full-scale experiments both in terms of cost and technical feasibility.

This paper details the experimental testing of a full scale aluminium cylindrical shell structure subject to long duration blast loading. Conducted in the Air Blast Tunnel facility at Foulness in Essex, UK [20], research examines detailed dynamic structural coupling of the cylinder within the flow field. Using advanced fibre optic instrumentation and high speed Phantom video photography, deformation and collapse of the shell was tracked upon arrival of the shock front and during the sustained dynamic pressure phase. High fidelity numerical modelling used to predict structural response *a priori* was shown to be inaccurate due to a number of assumptions pertaining to translational drag loads, explored previously by this author [8]. Updated using accurate blast pressure histories from the experiment, computational work demonstrated excellent agreement by comparison with gauge measurements and post-test observations. This research forms part of an on-going test programme examining a range of vessel configurations subject to long duration blast symptomatic of vapour cloud explosive loading.

2. Experimental procedure

The UK Air Blast Tunnel in Essex, UK, designed and constructed originally in 1964 is one of a very small number of elite facilities in the world capable of examining structural response subject to long

Table 1
Aluminium material properties.

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