Development and applications of a new pulse pressure loading test rig
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Abstract

A new test rig has been developed at the University of Liverpool Impact Research Centre for studying pulse pressure loading and response of a wide range of structures and materials. The versatility of the test rig to simulate different loading conditions and capability to generate controlled, repeatable pulse shapes is discussed. The test facility can be used to study both the fundamental and design aspects of blast loading effects on structures. A brief description of current projects using the test rig is also given.

1 Introduction

Structural loading and response arising from an explosion is relevant to a wide range of problems in, for example, the offshore, defence and transport industries, naval architecture, buildings, chemical and petrochemical process plant and the manufacture and storage of combustible dusts. Despite much research being carried out on structural response due to impact loads and impulsive loading,\(^1\) there is still a considerable lack of well defined experimental data on the response of structures subjected to pulse pressure loading, particularly with regard to failure, scaling and boundary conditions. Similarly, the loading experienced by structures resulting from a blast wave has been studied and reported in classical text books on the subject.\(^2,3\) This work, which is
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primarily based on military trials with high explosives and nuclear weapons, is concerned with structures at large distances from the source of the explosion and, therefore, relates to the loading characteristics of shock waves which can be readily predicted. In contrast, the loading experienced by structures within an explosion or near the explosion source, particularly if the explosion occurs in a confined area, is much more difficult to predict and measure. The majority of data on structural loading arising from an explosion relates to shock waves and distant objects. Only a few relevant experiments have been carried out to determine the loads on structures within confined areas.

Due to the hazardous nature and cost of full size explosion tests, a new test facility, Figure 1, has been developed at the University of Liverpool Impact Research Centre to study pulse pressure loading and response of a variety of structural components and materials under carefully controlled laboratory conditions. This will essentially enable a larger number and range of experiments to be carried out leading to a better understanding of both the fundamental and design aspects of pulse pressure loaded structures. The aim of this work is to improve design and assessment procedures and hence to improve safety of personnel and the general public.

This paper is concerned with the design and development of the pulse pressure loading test rig and its use in fundamental and applied research on blast loading effects on structures.

Figure 1: Pulse pressure loading test facility.
2 Test Facility

The design of the test rig was based on previous development work in the Impact Research Centre on a technique to simulate fast, rectangular shaped pressure pulses. The technique uses two pressure containers made from steel rings or cylinders and plastic drafting film or other suitable bursting diaphragm material to apply a pressure load equally to both sides of a test plate, the test plate being sandwiched between the two sets of rings. The pressure in the containers is suddenly released by bursting the membrane or diaphragm on each side, a small time interval apart, resulting in a differential pressure load being applied to the plate. The objective of this work was to develop a simple and effective technique for simulating blast loading with pressurised containers. The actual pressure pulse achieved with this technique was more triangular in shape than the rectangular shape desired and the duration was also longer than desired but, notwithstanding this, demonstrated that such techniques could be used satisfactorily to generate repeatable pulse pressure loading. Other studies were carried out using this technique to investigate the influence of bursting methods and different gases on the shape and duration of the pressure pulse. However, the original equipment in its present form was limited in the size and type of structure it could accommodate and the maximum pressure at which it could operate. A new test rig was therefore designed and built in the Impact Research Centre to enable a wider range of structures and loading conditions to be studied.

Figure 2: Schematic of test facility.
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2.1 Design and Construction

The new test rig has been designed initially to simulate dynamic overpressure loading conditions typically produced in a confined hydrocarbon explosion on plated structures up to 1 m square. The rig takes the form of a horizontal pressure vessel constructed in two halves which clamp together over a support plate to make a bolted joint as shown schematically in Figure 2. The support plate, which has a central 1 m square hole, divides the vessel into two pressure loading chambers and supports the test plate and clamp frame. Each chamber is capable of being pressurised independently or simultaneously and has a large 0.5 m diameter flanged nozzle to release the pressure in the chamber quickly by means of a bursting diaphragm. The support plate can also accommodate other fixing arrangements and structures. The whole assembly is suspended from a lifting frame. Geared trolleys with hoist attachments on the lifting frame enable the two chambers to be separated easily for access to the support plate. Additional items on the rig are observation windows for high speed photography and cable entries on the support plate for the various instrumentation lines.

![Figure 3: Principle of operation.](image-url)
2.2 Principle of Operation

The purpose of the pulse pressure loading rig is to apply controlled and repeatable pressure pulses to a structural member. This is achieved as follows. The structural member is fixed and sealed to the support plate and a thin diaphragm material is placed over the nozzle flanges making the two chambers air-tight. The air pressure in the chambers is increased equally at the same time to the test pressure, $P_1$ (4 bar maximum), so as not to impart a resultant load on the structural member. At time $t = 0$ in Figure 3, the pressure in one side of the vessel is suddenly released by bursting one of the diaphragms causing a difference in pressure across the member. At a pre-defined time later, $t = a$, the second diaphragm is burst, releasing the pressure in the other side of the vessel. The loading on the member is over by time $t = b$. The characteristic resultant pulse loading applied to structural member is given in Figure 4. This type of pressure pulse is representative of overpressure loading on a boundary wall in a partially confined hydrocarbon explosion. The test rig can also be used to apply static loading to a structural member.

![Figure 4](image-url)
2.3 Gas Dynamics

A one-dimensional flow model was used to estimate the blow-down times of the vessel and determine a suitable exit diameter. The model assumes that the flow is isentropic and unchoked. A graph of estimated blow-down time against chamber pressure for three gases, air, helium and carbon dioxide is given in Figure 5 together with experimental blow-down times for air and helium.

In practice, the way in which the diaphragm bursts affects the blow-down times and is more significant at lower test pressures, below 4 psi. At very low pressures, under 0.5 psi, it was necessary to adopt a different system of releasing the pressure. Balloons were used to block the exit area and burst using the same technique as used for the diaphragms, namely energising a fuse wire attached to the surface of the membrane. Other bursting methods have been investigated but this technique remains simple and effective.

The volume, pressure and mass of the gas and the exit area affect the blow-down times as shown in Figures 5-7. The time interval between the two chambers blowing down is a further controlling parameter. It is possible, therefore, to generate a wide range of load durations and pulse shapes by controlling these parameters. Also, the repeatability of the pressure pulse generated by this technique makes the test facility
particularly suitable for carrying out multiple tests to validate methods of analysis such as pseudo-shakedown.

![Graph showing variation of blow-down time with internal volume at different test pressures.](image)

Figure 6: Variation of blow-down time with internal volume at different test pressures.

### 2.4 Instrumentation

Test data is captured on high frequency (up to 25 MHz) transient recorders linked to high frequency sensors for the measurement of pressure, acceleration, displacement, strain, flow velocity and temperature. High speed video up to 1000 fps has been used to observe how the diaphragms burst. Dedicated instrumentation together with a PC based analysis centre ensures high quality data capture, storage and analysis.

### 3 Current Projects

The new test facility has attracted considerable support from EPSRC and industry. The following current projects being carried out in the Impact Research Centre show the range of problems capable of being investigated with the new test facility.

#### 3.1 Response of Stiffened Plates

The lack of experimental data on the response of stiffened plates to blast loading has led the oil and gas industries to rely on a mixture of analysis techniques and basic assumptions as to the inelastic structural behaviour,
material properties at high rates of loading and boundary conditions of these members. The aim of this work on 1 m square, 2 mm thick and 0.5 m square, 1 mm thick steel plates is to generate well defined data which can be used for relating scaled results to full size tests and to verify methods of analysis. The 1 m square plates are approximately one third of full size plates typically used on offshore platforms. The test programme consists of static and dynamic tests including multiple dynamic tests on clamped steel plates with and without stiffening ribs. An important aspect of this work is to evaluate the effect of in-plane restraint at the supports and edge displacements on the overall response of the plates. Further details of this project are given in reference 5.

![Graph showing variation in blow-down time with nozzle area at different test pressures.](image)

**Figure 7:** Variation in blow-down time with nozzle area at different test pressures.

### 3.2 Response of Glass Panels

City centre bombings demonstrate the vulnerability of buildings to the effects of an explosion, causing severe structural damage and putting personnel and the general public in and around buildings at risk. Glazing panels which shatter in the blast are the main cause of injury due to the high velocity fragments produced. The test facility is being used to investigate the structural behaviour of architectural glazing systems subjected to abnormal dynamic pressure loading arising from an accidental explosion or bomb blast. The type of glazing system studied in this work is supported at a discrete number of points unlike conventional glazing systems which are usually supported along all edges. The results will be used to generate design data for use by architects and building engineers involved in the design of glazing systems to meet blast loading
requirements and hence to improve safety in the built environment. Further details of this project are given in reference 6.

3.3 Smart Technologies

Solid structures cannot change their characteristics easily or quickly enough in a dynamic loading situation. An electrorheological fluid, on the other hand, exhibits a massive and reversible change in its effective viscosity when electrically energised, this process taking place in the order of a few milliseconds. Feasibility studies are being carried out to exploit the novel application of electrorheological fluid devices to structural members in order to control deformations and load transfer in these members and to adapt to different loading conditions. These devices would be employed in a system either in order to control the distribution of stress and strain throughout the members or to control the stiffness of the attachments. Controlled experiments will be carried out on the new test facility to assess the application of electrorheological fluids to the rapid modification of the structural characteristics of blast loaded members with a view to improving structural efficiency.

![Figure 8: Test rig arrangement to study received structural loading.](image-url)
3.4 Received Loading

At the interface between combustion science and structural engineering there is an uncertain and under-researched area, namely the loading transmitted to a structure arising from an explosion, particularly in confined explosions. Basic experiments on simple shaped rigid objects are being used to develop a detailed understanding of the loads experienced by structures in a confined gas or dust explosion. This will lead to improved design and assessment of structures and equipment in the offshore and process industries.

![Diagram](a) Pulse profiles measured on an object located outside the test rig - (a) low vessel pressure (b) high vessel pressure.
The test rig will be used in a different mode to that used in the first two projects. In this project the test facility will be operated in such a way as to simulate transient pressure and fluid loading of the type produced in a confined explosion. An instrumented obstacle located inside the vessel across the venting area as illustrated in Figure 8, or just outside the venting area will be subjected to the transient dynamic pressure and fluid loading produced when the vessel suddenly blows down. The downstream pressure profiles recorded on a rigid body outside the vessel at low and high blow-down pressures are given in Figure 9. This work will also enable the characterisation of loading on buildings arising from a vapour cloud explosion.

4 Concluding Comments

A new, versatile test facility has been developed in the University of Liverpool which is capable of producing repeatable and uniform pulse pressure loading on a structural member by virtue of a dynamic pressure gradient across the member created by the timed blow-down of back-to-back pressure loading chambers. The facility can also be operated in such a way as to simulate transient pressure and fluid loading on a structural component, typical of the loading experienced by an obstacle inside the region of a confined, vented explosion or outside the region of the explosion. The ability to produce controlled, repeatable pulse shapes of different forms to simulate different loading situations makes this test facility suitable for studying a wide range of blast engineering problems in various industries. It is particularly suitable and cost-effective for generating well defined experimental data for use in both the fundamental and design aspects of blast loading effects on structures. The results produced by this test facility can be used to validate methods of analysis, to calibrate computer models, to improve hazards evaluation procedures and to improve the blast resistant design of structures.

References

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