Nonlinear structural consequences of plates with apertures under pulse pressure loads: an experimental and numerical study

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Abstract

This paper investigates a complex problem involving large inelastic deformation in thin clamped square ductile plates with a variety of apertures. Thin plated structures are used in a wide range of situations where the possibility of loading from a gas explosion or an IED should be considered in the design, e.g. deck plating and bulk heads on ships and offshore platforms to aircraft structure applications. The material used is Docol form 01, a highly ductile cold rolled mild steel, ideal for impact applications. The study utilizes a differential pressure device developed at the University of Liverpool Impact Research Centre capable of producing repeatable uniform transient pressure loading on 0.5 m by 0.5 m plate specimens. Structural response was investigated at two nominal pressure levels for plates with varying apertures. The effect of any pressure variance occurring around these openings in relation to global loading on the plates was also investigated. Extensive material tests were performed and parameters used in a Cowper-Symonds constitutive model. A series of FEA simulations of the blast loading was also conducted and compared with the experimental data for validation. Initial studies show a good correlation between experimental and numerical simulations.
Keywords: transient loading, thin steel plates with holes, sub-scale tests, numerical simulations.

1 Introduction

Explosion events occur across different industries, when producing, processing, storing or transporting volatile materials. These range from bakeries to

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processing of hydrocarbons. Protection and safety are now an integral part of structural design and as such, it is very important to understand material response to transient loading from an explosion or blast. This paper considers the effects of penetrations in plated deck structures found on offshore topsides and ship bulkheads so as to provide improved limit state assessment criteria to industry on the design of deck structures under blast loading [1–4].

In particular, studies of plates with openings have had very little attention in the past. Langdon *et al*. [5] recently investigated plates with small openings; however this focused on using perforations to mitigate the blast loading rather than their effects on the plate. Li *et al*. [6] studied the explosion resistance of square plates with openings for venting dust explosions for applications in the process industry, however very limited details were provided. Jain [7] investigated the effect of the hole aspect ratio of rectangular plates on the normal stress, shear stress and deflection in the transverse direction when loaded statically. However, to the authors' knowledge limited experimental studies have considered dynamic transverse loading on plates with openings. Rakvag *et al*. [8] recently conducted a series of transient pressure test on thin plates with pre-formed holes to simulate combined blast and fragmentation in a simplified manner. This highlighted that the pressure immediately within the vicinity of the opening could be of higher pressure than that acting on the rest of the plate.

2 Experimentation

This study utilizes a differential pressure device developed at the University of Liverpool Impact Research Centre, as depicted in figure 1. It is capable of producing repeatable uniform transient pulse pressure loading on 0.5 m by 0.5 m (loaded area). In this study the plates were mild steel (Docol form 01)

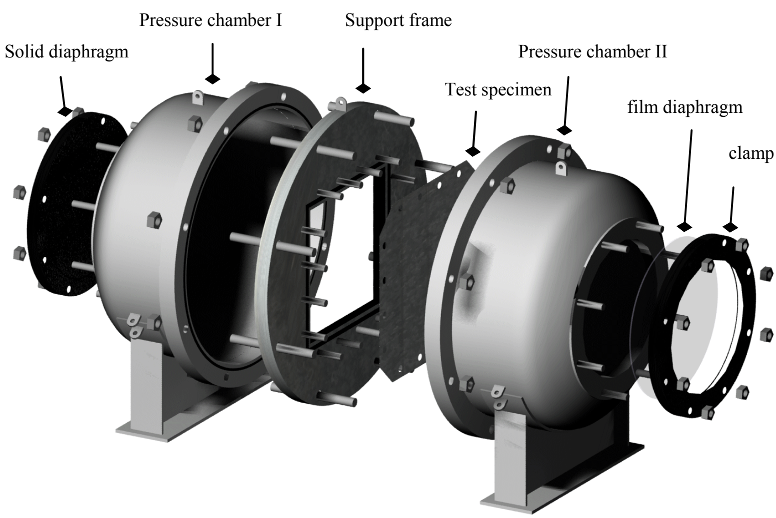

Figure 1: Exploded view of pulse pressure loading rig (PPLR).

nominally 1.1 mm thick corresponding to a loaded area scaling of approximately 1:8. The facility is particularly efficient for experimental studies of both a fundamental and applied nature. The device can impart typically 200 kPa under 10 ms which, at this scale, can simulate representative rise in overpressure produced by a semi-confined gas explosion.

2.1 Test plates

Six different apertures were used in the blast loading experiments. The geometry of the plates is given in Figure 2. Each plate was clamped all around the boundary with equi-spaced studs each torqued to the same value of 100 Nm. The studs were 20 mm in diameter and the clamping holes 22 mm in diameter. The geometries of the holes were chosen to represent idealized apertures in bulkheads on ship structures.

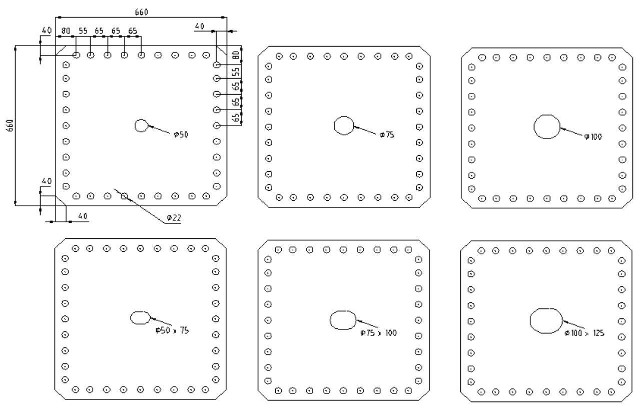

Figure 2: Square plate specimens with circular and extended circular holes.

The outer dimensions for each plate are 660 mm by 660 mm, while the area exposed to the pressure load is 500 mm by 500 mm minus the area of the hole. Each plate has a nominal thickness of 1.1 mm

2.2 Pressure-time curves

Two nominal peak pressure loads of 172.4 kPa (25 psi) and 344.8 kPa (50 psi) were applied across the range of plate specimens. This produced permanent deformation in the plates that could be measured while the plates were still in post-test situ. A summary of the test results for these plates is given in Table 1.

2.3 Blast test method

These transient pressure loadings were created by placing a solid diaphragm on Chamber I, and a thin burstable diaphragm on Chamber II, as shown in Figure 1. Both chambers were then simultaneous filled with air to ensure the plate was not

Table 1: Test data for square plates with circular holes loaded to nominally 172.4 kPa (25 psi) and 344.8 kPa (50 psi).

Hole geometry (mm)	Hole area as ratio wrt ϕ50 hole	Hole area as % of plate area	Rise time (msec)	Peak pressure (kPa) [psi]	Load duration (msec)	Final centre disp. (mm)
ϕ50	1.00	0.78	5.3	184.8 [26.8]	677	15.0
			13.2	344.05 [49.9]	737	23.3
ϕ50x75	1.64	1.29	7.4	179.3 [26.0]	463	12.4
			12.6	346.1 [50.2]	598	22.4
ϕ75	2.25	1.75	5.5	181.3 [26.3]	318	13.7
			9.6	337.2 [48.9]	437	22.8
ϕ75x100	3.20	2.51	7.0	177.2 [25.7]	229	12.4
			10.2	330.9 [48.0]	311	23.0
ϕ100	4.00	3.14	6.0	176.5 [25.6]	189	13.7
			13.1	322.0 [46.7]	243	21.3
ϕ100x125	5.27	4.14	5.7	171.0 [24.8]	140	14.6
			13.0	312.3 [45.3]	151	22.1

pre-loaded prior to the desired pressure level ($t<0$). Once the pressure level was reached ($t=0$) fuse wire was energised around the circumference of the burstable thin diaphragm, producing a controlled release of the internal pressure back to atmospheric pressure ($t>0$).

As the diaphragm in chamber I is ruptured, ($t=0$) a dynamic pressure gradient is created across the test piece. This is created as the area of pressure escaping through the burst diaphragm is far greater than the pressure escaping through the aperture in the plates. This produces a triangular pressure pulse (figure 3) which gives a scaled overpressure typically imparted to a full-size structure due to a hydrocarbon explosion.

2.4 Representativeness of loading

The loading generated by the pulse pressure rig is generally idealized to that characterized by a confined gas explosion which has a finite rise time and decay

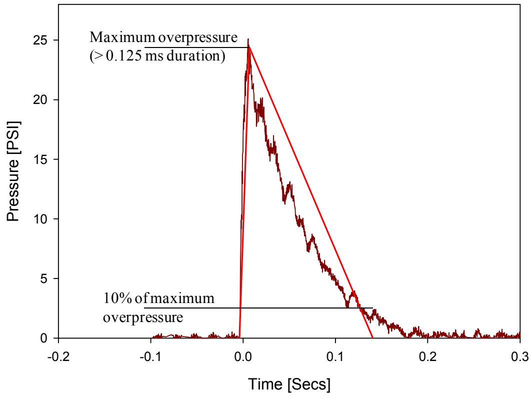

Figure 3: Pressure-time history for plate with ϕ100 by 125 mm hole showing construction of idealised triangular pulse load (pmax=24.8 psi, tr=5.7 msec, td=140 msec) used in the numerical modelling.

by the sequential rapid blow-down of the two chambers a timed interval apart. The rise time is the most significant part of the loading history which is dependent on the blow-down time. To maximise the impulse only one side of the chamber (II) was depressurised. Using a solid plate then depressurising one side and then the other can create an equal rise time and decay time. However with plates with holes this may be slightly different as air can escape through the hole during the first blow-down and before the second is initiated. This requires future work for clarification.

3 Experimental results

A total of 12 tests were conducted, applying the two nominal pressure levels to each aperture. The permanent midpoint deflections of the tested plates are summarized in Table 1.

Pressure gauges (PGs) recorded the side-on pressure on the plate specimens either side [I and II] from a total of four pressure gauges, see figure 4. The load was then approximated as the pressure difference between these and assumed to be uniform across the entire plate, depicted in figure 5. Czujko [9] commented that pressure distributions in a vented vessel explosion are often quite uniform.

There is little or no variation in the pressure recordings from the two sets of gauges located on the top and side of the support plate. The rise to peak pressure appears almost instantaneous due to the scale used to capture the full pressure-time curve but there is a finite rise.

It can be seen that there is no significant variation over the range of hole size for a given nominal test pressure; some variation may be caused by the small differences in peak pressure and rise time. The decrease in stiffness associated with the increasing area of the holes is more than compensated for by the decrease in the load due to the reduced loading area.

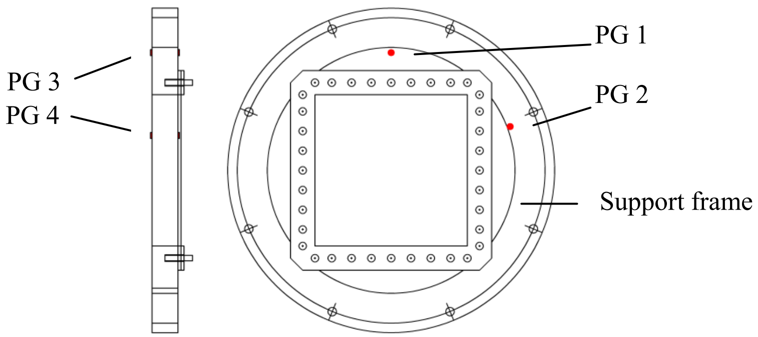

Figure 4: Schematic of the positions of the pressure gauges.

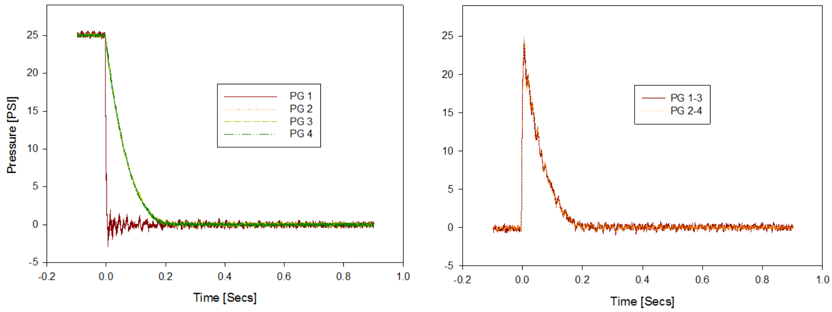

Figure 5: Assumption of the pressure loading.

Visual inspection of the plates identified plastic hinges at the edges, but no plastic hinges within the plates.

4 Numerical modelling

A series of numerical simulation were performed to simulate the blast loading of the plates using ANSYS Explicit Dynamics, specifically designed for non-linear dynamic problems. Lagrange, ALE, EULER and mesh free solvers can be used to investigate such problems. The Lagrangian solver was utilised for this problem. It divides the structure up into segments that are interconnected by nodes which move with the material as it deforms. The pressure loading was taken from pressure gauges on the PPLR as described in section 3 and idealised as a triangular pulse (see figure 3). This pressure was applied uniformly to the shell elements and always normal to the surface of the plate.

4.1 Geometry and boundary conditions

Due to the complexity of modelling non-linear behaviour, such as imparted by blast loads several simplifications were made to the NLFEA model to improve efficiency and accuracy of results.

- Only ¼ section of the panel was modelled – taking advantage of symmetry
- 4 node shell181 elements were used – typical for thin walled applications
- Blast load is idealised as a triangular pressure pulse load.

To accurately describe the behaviour of the plate numerically, a true representation of the experimental boundary conditions must be simulated, as shown in figure 6.

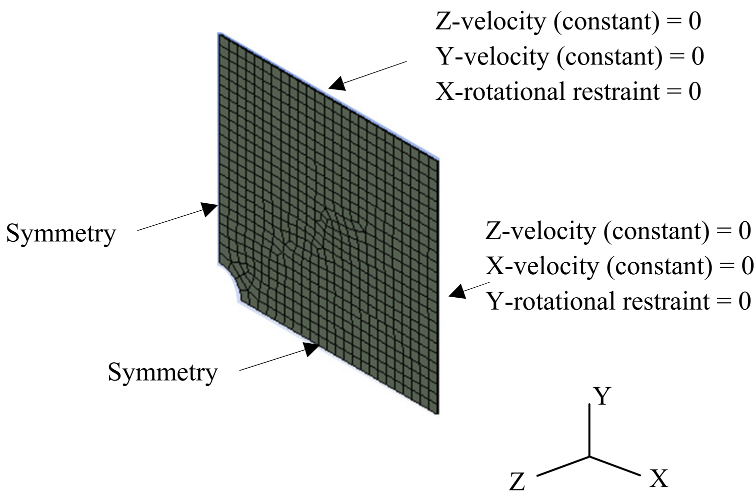

Figure 6: Typical finite element geometry of blast specimen with ¼ symmetry about the X and Y-axis.

These boundary conditions allow membrane stretching by virtue of the in-plane restraint which is the primary load bearing mode is these thin plates.

4.2 Mesh refinement studies

A mesh sensitivity study was firstly conducted to investigate how the mesh influences the solution, in relation to the midpoint deflection. Quarter-symmetric boundary conditions were utilised to save on computational time.

The experimental pressure-time curve chosen was the 100 mm aperture at 344.8 kPa (50 psi). This caused the plate to undergo one of the largest deformation and thus would be more likely to be mesh sensitive.

From this initial study it was established that a relatively coarse mesh could accurately describe the global response of the plate. 10 mm mesh was chosen for this study.

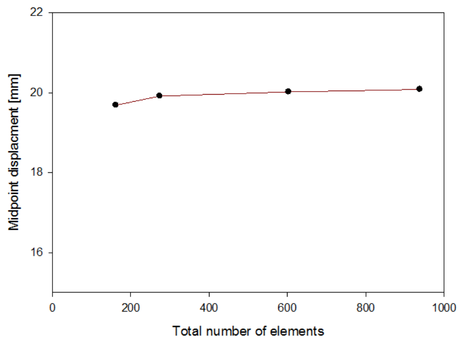

Figure 7: Mesh sensitivity comparing 20, 15, 10 and 8 mm element size.

4.3 Material properties

Docol form 01 is highly ductile cold rolled mild steel which can be used for a wide variety of applications, ideal for impact.

4.3.1 Strain rate sensitivity and strain hardening

During a blast event, such as on a topside structure, components have to absorb the kinetic energy typically within 20–50 ms [10]. Under such conditions the strain hardening and strain rate hardening have a crucial influence on the behavioural response of the structure. Therefore these must be accurately modelled in order to understand and predict the blast response.

Quasi-static uniaxial tensile tests were conducted to obtain the true stress-strain parameters required to describe the strain hardening effect A, B and n, are described in eqn. (1) and are valid until the onset of necking. These curves were assumed to be isothermal which is valid for low strain rates.

Equation (2) describes the strain rate effects of the material and this was determined by conducting a series of dynamic uniaxial tensile tests using a Split Hopkinson Tension Bar (SHTB) at rates between 5 and 534 s^{-1} all conducted at room temperature. The Cowper-Symonds coefficients were obtained as D=298.02 and q=4.89.

$$\sigma = A + B\varepsilon^{n} \quad (1)$$

$$1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{1/q} \quad (2)$$

These values are similar to other experimental work conducted on mild steel [5, 11].

4.3.2 Temperature effects

Chung [12] and Langdon *et al.* [13] impulsively blast loaded a series of mild steel plates and investigated the response over the entire plate and at the plate centre. Results highlighted the benefits of including temperature effects into the analysis, specifically for predicting the onset of tearing. Chung also concluded that temperature effects made very little difference in predicting Mode I response. From inspecting the clamped plates within this experimental work it could be seen that no tearing or thinning of the plates occurred. Initial calculations of the strain rates applied to the plates in this work are in the order of 1 s^{-1}. With these expected strains and strain rates in the experiments, adiabatic heating of the material due to plastic dissipation is not expected to have any significant influence on the material behaviour. As such, temperature effects have been neglected in the numerical modelling.

5 Numerical results

It can be seen from Table 2 that the numerical simulations are able to produce the experimental permanent deflection with reasonable accuracy, the maximum difference being 15%. All numerical simulations under-estimated the final mid-point deflections. This is probably due to a combination of simplifying the transient pressure load as uniform load and the slight slippage which occurred around the boundary conditions in the experimental work. Even slippage of the order of 0.1 mm can have a marked difference to the final displacement.

Table 2: Numerical predictions of the final midpoint deflection for 172.4 kPa (25 psi) and 344.8 kPa (50 psi) loaded plates against actual values.

Hole geometry (mm)	Experimental disp. (mm) at 172.4 kPa	Numerical disp. (mm) at 172.4 kPa	Experimental disp. (mm) at 344.8 kPa	Numerical disp. (mm) at 344.8 kPa
ϕ50	15.0	11.6	23.3	19.9
ϕ50x75	12.4	11.8	22.4	20.8
ϕ75	13.7	11.5	22.8	20.0
ϕ75x100	12.4	11.5	23.0	20.9
ϕ100	13.7	11.4	21.3	20.02
ϕ100x125	14.6	11.8	22.1	20.2

It shows that the final global deformation is very similar for all cases. This is caused by a reduced stiffness as the aperture size increases, combined with a reduced peak pressure as the loading duration is dependent on the blow-down time, which in turn is dependent on the aperture size. Figure 8 shows the equivalent plastic strain field around the apertures. Deflections in the plates are approximately 20 times that of the order of the plate thickness however the plastic strains are only small. The maximum plastic strain of 3.7% occurs locally.

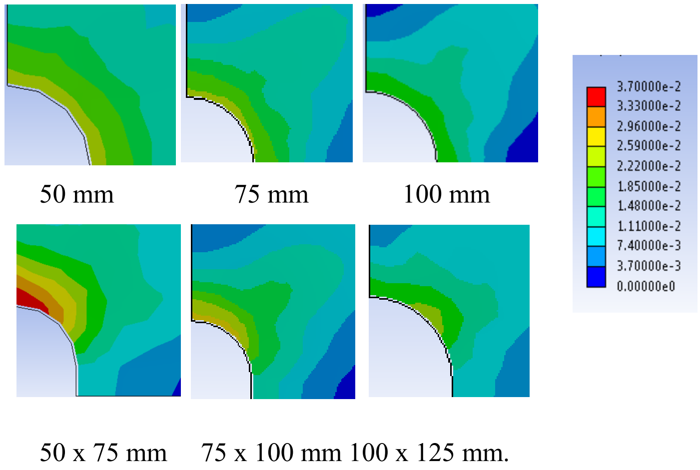

Figure 8: Equivalent plastic strain plotted on the deformed plates around the apertures after 344.8 kPa (50 psi) nominal pressure loading.

6 Conclusions

A study of plates with perforations will benefit the offshore industry in terms of improved design guidance and optimisation of deck plates, blast walls and blast relief panels. New novel small-scale (1:8) dynamic pressure tests on 0.5 m square plates with central circular and extended circular holes has been conducted at nominal test pressure of 172.4 kPa (25 psi) and 344.8 kPa (50 psi), simulating an extreme over-pressure event. The numerical modelling using the Langrangian solver and an idealised pressure-time history gave more than acceptable results when compared with the test data for the global response. Future work will consider ALE and fluid-structure interaction using numerical finite element methods.

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