Failure characterization of clamped aluminium plates under pulse pressure loading

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Abstract

An experimental study has been conducted to characterize the failure of pulse loaded aluminium plates with clamped boundary conditions. The plates were 0.5 m square by 1 mm and 0.5 mm thick. The aim of this work was to induce tensile rupture of the plates at the boundary, a mode II type failure, using novel dynamic loading techniques. Previous work has focused on the characterization of impulsively loaded plates. The purpose of this paper is to present the results of static and dynamic tests on thin, clamped aluminium plates and show that the same divisions of failure previously observed in experiments with impulsive loading also applies to the pulse pressure loading of plates. The necking process which occurs before the onset of mode II failure was observed around the entire boundary of the plates which failed by large inelastic deformation, characterized as mode Ib failure. In all cases, tearing of the plates occurred along three edges, characterized as mode II* failure. While aluminium is normally regarded as a strain rate insensitive material, the results suggest that the dynamic tests were influenced by rate effects. The failure surface of the ruptured plates was also inspected using scanning electron microscopy and confirmed the mode II* characterization observed in the tests. An assumed-modes, elastic-plastic analysis together with a simple strain based failure criterion was used to predict the ultimate capacity of the ruptured plates and gave good agreement.
Notation

- $C$: Generalised transverse displacement
- $E$: Modulus of elasticity
- $\varepsilon$: Total strain
- $\varepsilon_m$: Membrane strain
- $h$: Plate thickness
- $\kappa$: Curvature
- $l$: Plastic hinge length
- $p$: Pressure
- $w$: Transverse displacement
- $x, y$: Model co-ordinates (origin at centre)
- $X, Y$: One-quarter symmetry model dimensions

Introduction

The response of structures and structural components to extreme loading events such as an explosion is relevant to many different industries, including the aerospace, offshore, defence, and nuclear industries. The failure and deformation behaviour of plates need to be understood to improve the design of containment structures and offshore platforms, for example, against blast loading. Much of the research performed on structural response has concentrated on impulsive loading. Limited experimental data is available on the response of structures to pulse pressure loading, particularly in the dynamic loading range which is very difficult to repeat using a flammable gas or explosive substance.

Menkes and Opat [1] were the first to define failure modes as a result of experiments on impulsively loaded clamped aluminium beams: mode I – large inelastic deformation, mode II – tensile tearing at the support and mode III – transverse shear failure. In recent studies on square [2-4] and circular [5] plates subjected to impulsive loading, similar failure modes have been observed. One of the aims of the present work was to show that the same divisions of the failure criteria observed in the experiments with impulsive loading could be applied to the pulse pressure loading of plates.

Mode I failure

The large inelastic deformation of clamped beams and plates is associated with a mode I type response. It was observed by Nurick et. al. that different phases in the necking process at the clamped boundary occurs before the onset of mode II failure and hence the criterion of general mode I response was redefined [2] as shown in Table 1.
Table 1: Subdivisions of failure modes made by Nurick et. al. [2,3]

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Subdivisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I</td>
<td></td>
</tr>
<tr>
<td>large inelastic</td>
<td>I large inelastic deformation, no necking at the support</td>
</tr>
<tr>
<td>deformation</td>
<td>Ia large inelastic deformation with necking around part of the support</td>
</tr>
<tr>
<td></td>
<td>Ib large inelastic deformation with necking around the entire support</td>
</tr>
<tr>
<td>Mode II</td>
<td></td>
</tr>
<tr>
<td>tensile tearing</td>
<td>II* tensile tearing at the outer fibres over part of the boundary,</td>
</tr>
<tr>
<td>at the support</td>
<td>the transition between mode I and mode II failure</td>
</tr>
<tr>
<td></td>
<td>Ila tensile tearing around the entire support with increasing centre deflection with increasing applied impulse</td>
</tr>
<tr>
<td></td>
<td>IIb tensile tearing around the entire support with decreasing centre deflection with increasing applied impulse</td>
</tr>
</tbody>
</table>

Mode II failure

Beams and plates exhibit tensile tearing at the clamped boundary during mode II type response. For a uniform pulse load, the highest strains in a clamped plate occur at the mid-span of the clamped edge. Hence, there are four possible areas on the clamped boundary of the plate where tensile tearing is most likely to initiate. This failure mode has been further subdivided as a result of research into the deformation of impulsively loaded square plates [3,4] as shown in Table 1.

Pulse pressure loading rig

The University of Liverpool Impact Research Centre has developed a facility to study the response of structures, structural components and materials to pulse pressure loading. The test rig is capable of producing a repeatable, uniform pulse with a triangular pressure-time history. The test facility is shown schematically in Figure 1.

The test rig consists of two back-to-back pressure chambers which can be independently or simultaneously pressurised, depending upon the required mode of operation. A support plate is used to clamp the test piece in position, sandwiched between the two halves of the pressure vessel. In this series of tests, a reduction plate was used to accommodate the 0.5 m square plates. A 0.5 m diameter flanged nozzle in each chamber allows rapid blow-down of each chamber via a bursting diaphragm system.

Experimental techniques

Pressure tests using the pulse pressure loading rig

The square aluminium plates had 32 equi-spaced holes for location and clamping, providing in-plane and rotational restraint at the edges. Although it is possible for some slippage to occur due to the clearance between the plate holes
and the studs in the reduction plate, no evidence of this was observed during the tests.

![Diagram of test facility](image)

Figure 1: Schematic construction of the test facility

**Static pressure tests**
In the static mode of operation, cover plates are fitted to the nozzle flanges; this allows the vessel to be pressurised until the plate ruptures. One chamber is gradually pressurised while the other is vented to atmosphere. Piezoresistive pressure transducers measured the pressure on the plate and linear voltage displacement transducers (LVDTs) were attached at two points on the plate. A single static test was conducted on each plate thickness. The 0.5 mm plate test was designated ASR051 and the 1 mm thick plate test was designated ASR052.

**Dynamic pressure tests**
In the dynamic test mode, rings are used to clamp a diaphragm made from multiple layers of draughting film to the nozzle flanges, creating an air-tight pressure chamber on either side of the test piece. The two chambers are then pressurised simultaneously, to ensure that no resultant load is applied to the specimen, up to the test pressure. At test pressure, one side is rapidly depressurised followed, a timed interval later, by the other side. This is achieved by attaching fuse wire around the perimeter of the diaphragm. When the fuse wire is energised by an electric current the diaphragm instantaneously ruptures. The operation principle is illustrated in Figure 2. Both sides of the vessel return to atmospheric pressure when the loading is over.

Four dynamic tests were carried out on the 1 mm thick aluminium plates, designated ADR051, ADR052, ADR053 and ADR055. Each test involved a new plate and each time the test pressure was increased until the plate ruptured. The plate was orientated left to right corresponding to the rolling direction (longitudinal) and top to bottom corresponding to the transverse direction of the plate material. The pressure on both sides of the plate was measured using
piezoresistive pressure transducers. The LVDTs were not used in the dynamic tests to avoid damage to the transducers.

![Figure 2: Principle of operation of the pulse pressure loading rig](image)

**Failure criterion**

A strain-based criterion was used to model tensile tearing at the plate boundary. This approach is based on the rigid-plastic analysis of clamped beams having a rectangular cross-section [6,7]. The total strain to cause tearing of the outer fibres is considered to be the sum of the axial strain and the strain due to curvature, given by

\[ \varepsilon = \varepsilon_m + \frac{h \kappa}{2} = \varepsilon_m + \frac{h \theta}{2l}. \]

where \( h \) is the plate thickness, \( \kappa \) is the curvature, \( \theta \) is the rotation at the plate boundary and \( l \) is the hinge length.

**Analytical model**

A theoretical model based on the assumed-modes, elastic-plastic method [8] was developed which predicts the maximum dynamic deflection and the permanent deformation of the test plates with mode I response and predicts the ultimate capacity of the test plate with mode II response [9]. The shape function given in eqn (2) was used to represent the global elastic-plastic deformation of the clamped plate under uniform lateral loading, illustrated in Figure 3.

Strips of finite width lying in the orthogonal axes of the plate were used to model the behaviour of the plate, as shown in Figure 4. These elements were treated as one-dimensional beams. Energy methods were used to formulate the elastic-plastic strain energy of the multi-member models in the analysis. This included elastic-plastic flexural and membrane strain energy.

A 5 by 5 grid of elements was used to represent one quarter of the plate. Non-linear translational springs were used to model the in-plane restraint at the boundaries of the plate, one spring element per strip. The maximum resistance was determined from the yield stress of the material and the spring stiffness was set to give full in-plane restraint of the plate. The energy terms were substituted into Lagrange's equation which was solved using a fifth-order Runge-Kutta numerical integration scheme.
\[ w = C \cos \left( \frac{\pi x}{2X} \right) \cos \left( \frac{\pi y}{2Y} \right) \]  

(2)

**Figure 3:** Assumed mode of deformation of laterally loaded plates

**Figure 4:** Structural model of the test plate (one-quarter symmetry)

**Results and discussion**

**Material characterisation**

To characterise the mechanical properties of the plate, a series of static uniaxial tensile tests were performed in the transverse and longitudinal directions for each thickness. A small number of dynamic tensile tests were performed on the 1 mm
thick material to give an indication of possible strain rate sensitivity. Table 2 contains the static tensile test results.

The static tensile test results show that the transverse specimens exhibited a lower yield stress and ultimate tensile stress than the longitudinal specimens, suggesting that rupture initiation is more likely to occur along the bottom or top of the plate. However, the higher ductility in the transverse direction suggests that rupture initiation is more likely to occur along the left or right side of the plate. The dynamic tensile test results indicated that the material could be moderately strain rate sensitive, although the number of samples tested was too small to be conclusive. The static tensile test results for the 0.5 mm thick samples showed close agreement in the two directions.

### Table 2: Static tensile test results, gauge length = 90 mm

<table>
<thead>
<tr>
<th>Thickness, h (mm)</th>
<th>Grain Orientation</th>
<th>E (GPa)</th>
<th>0.2% Proof Stress (MPa)</th>
<th>UTS (MPa)</th>
<th>Ductility (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Longitudinal</td>
<td>68.25</td>
<td>106.4</td>
<td>113.7</td>
<td>4.39</td>
</tr>
<tr>
<td>1</td>
<td>Transverse</td>
<td>66.0</td>
<td>85.6</td>
<td>96.4</td>
<td>7.64</td>
</tr>
<tr>
<td>0.5</td>
<td>Longitudinal</td>
<td>73.8</td>
<td>129</td>
<td>137.3</td>
<td>4.06</td>
</tr>
<tr>
<td>0.5</td>
<td>Transverse</td>
<td>71.7</td>
<td>126.7</td>
<td>138.1</td>
<td>3.43</td>
</tr>
</tbody>
</table>

**Static pressure tests**

Tearing occurred down the left and right sides of both plates and along the bottom of the plate, classed as a mode II* type response. The 0.5 mm and the 1 mm plates failed at pressures of 0.94 bar and 1.25 bar respectively. The plates failed with similar central deflections (22.7 mm for the 0.5 mm thickness and 21.2 mm for the 1 mm thickness). The post-test inspection of the plates suggested that rupture initiated at the mid-point of the bottom edge and spread to the corners and up the left and right sides of the plate stopping at the top edge.

**Dynamic pressure tests**

Four dynamic tests were performed on the 1 mm thick plates. The LVDTs were removed during these tests, therefore no transient displacement measurements were taken. The dynamic test results are summarised in Table 3 and are reported more fully in [9]. Three of the plates failed by large inelastic deformation, mode I type response, with a maximum permanent displacement to thickness ratio of 26.3. One plate (ADR055) failed by tensile tearing along the bottom clamped edge and along the left and right clamped edges, a mode II* type response. The anticipated test pressure was 1.7 bar, but from the pulse shape it was clear that the plate failed (ruptured) at 1.5 bar. ADR055 was orientated in the same way as static plate (ASR052) with regard to the longitudinal and transverse material directions. The ruptured plate in the test rig is shown Figure 5.

It is interesting to note that the deformation of these plates was more severe than the equivalent statically loaded plate. A further interesting feature of these tests is that the deformation of the pulse loaded plates, based on the permanent
deformation derived from the measured rotation of the plate at the edge, exceeded the deformation at which failure occurred in the statically loaded plate. This suggests that the pulse loaded plates were influenced by rate effects although aluminium is not normally regarded as a rate sensitive material.

Table 3: Summary of dynamic pressure test results

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Duration (ms)</th>
<th>Pulse Pressure (bar)</th>
<th>Perm. Def. (mm)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADR051</td>
<td>54</td>
<td>0.85</td>
<td>15.29¹</td>
<td>Mode Ib failure</td>
</tr>
<tr>
<td>ADR052</td>
<td>64</td>
<td>1.0</td>
<td>20.77¹</td>
<td>Mode Ib failure</td>
</tr>
<tr>
<td>ADR053</td>
<td>81</td>
<td>1.25</td>
<td>26.29¹</td>
<td>Mode Ib failure</td>
</tr>
<tr>
<td>ADR055</td>
<td>52</td>
<td>1.5</td>
<td>-</td>
<td>Mode II* failure</td>
</tr>
</tbody>
</table>

¹ Permanent deformation estimated from SEM results

Figure 5: Ruptured test plate ADR055, clamp frame and support plate of PPLR

Materials failure analysis

Samples were taken from the ruptured plates and their failure surfaces examined using a Scanning Electron Microscope (SEM). The plates all had similar failure surfaces. Plate samples showed ductile dimples elongated in the direction of shear. This analysis confirmed that the failure mode of the ruptured plates was that of tensile tearing, classified as a mode II* failure.

Partial necking along the clamped edges of the other failed plates was observed. The rotation angle of the plastic hinges at the clamped boundary and the plastic hinge length were measured using the SEM. The rotation angle was found to increase with increasing test pressure and the plastic hinge length \( l \) was measured to be approximately 3 mm \( (l = 3h) \). The test plates which did not rupture were classified as failing according to the mode Ib criterion, namely large inelastic deformation with necking around the entire support.
Analytical model

Only the permanent deformation as derived from the SEM results and equation (2) and the critical load of the test plates could be compared with the analytical results given in Table 5. The loading was approximated to a simple triangular load-time function with a finite rise. From the material test results, a static flow stress of 95 MPa and failure strain of 5% were used in the analysis. It was assumed that strain rate sensitivity was negligible. Other material constants used in the analysis were 67 GPa for the elastic modulus and 2700 kg/m$^3$ for the density of the plates. Since the plates were highly restrained, a high in-plane stiffness of $10^6$ kN/m was applied. In order to predict the critical failure load, a plastic hinge length $l$ of 3 mm ($l = 3h$) was used, this being the approximate measured hinge length from the SEM analysis. A five by five finite element model was used for all the predictions.

The analytical and derived experimental permanent deflections of the plate in Table 5 do not compare well. However, the analytical maximum deflections appear more convincing when compared with the derived experimental permanent deflections. The analysis predicted a failure (tensile tearing) load of 1.46 bar for test plate ADR055. This plate actually failed at around 1.5 bar. As the values for the static flow stress, plastic hinge length and critical failure strain were determined approximately from the SEM and tensile test results, a limited study of the sensitivity of these parameters was conducted. The parameter study indicated that failure strain and hinge length have a significant effect on failure load. This limited study was able, for $2h \leq l \leq 4h$, to bound the solution to the critical tensile failure of the clamped square plates under uniform pulse pressure loads.

Conclusions

The failure modes of thin, square clamped aluminium plates subjected to static and pulse pressure loading were examined using novel experimental techniques and scanning electron microscopy (SEM). The 0.5 mm and 1 mm thick statically loaded plates ruptured at pressures of 0.94 bar and 1.25 bar respectively, with tearing along three edges of the plates. This was classed as a mode II* response (tensile tearing over part of the support). Rupture of the 1 mm thick pulse loaded plate occurred at a pressure of 1.5 bar with a rise time of approximately 30 msec. This mode of failure was also classed as a mode II* response with tearing down three edges of the plate. The other plates exhibited large inelastic deformation with necking around the entire support, classed as a mode Ib response. It transpires that the classification of failure for impulsively loaded plates also applies to plates subjected to pulse pressure loading. While aluminium is not normally regarded as a rate sensitive material, the test results showed that the pulse loaded plates were influenced to a degree by rate effects. The deformation at failure (mode II*) of the statically loaded 1 mm thick plate was less than the deformation of the equivalent pulse loaded plate (mode Ib). The microstructure
examination of the failed (ruptured) plates revealed that all the plates had similar characteristic tensile failure surfaces and confirmed the mode II* classification.

The assumed-modes analytical approach used to predict the critical failure load of the pulse loaded plates gave encouraging results and inspires confidence in developing the approach for a wider range of structures and materials. A simple strain-based failure criterion worked well in this case as the critical failure strain and plastic hinge length were determined from the tensile test and SEM results respectively. Notwithstanding this, the model was able to bound the solution to the critical tensile failure of the square clamped plate under pulse pressure loading for \(2h \leq l \leq 4h\), where \(h\) is the plate thickness and \(l\) is the plastic hinge length.

Table 5: Comparison of analytical and experimental results

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Load (bar)</th>
<th>Idealised (t_0) (msec)</th>
<th>Idealised (t_u) (msec)</th>
<th>Analytical Max. Def. (mm)</th>
<th>Time at Max. (msec)</th>
<th>Analytical Perm. Def. (mm)</th>
<th>Expt. Perm. Def. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADR051</td>
<td>0.85</td>
<td>30</td>
<td>55</td>
<td>22.2</td>
<td>29.7</td>
<td>6.6</td>
<td>15.3</td>
</tr>
<tr>
<td>ADR052</td>
<td>1.0</td>
<td>35</td>
<td>65</td>
<td>24.5</td>
<td>33.4</td>
<td>8.1</td>
<td>20.8</td>
</tr>
<tr>
<td>ADR053</td>
<td>1.25</td>
<td>35</td>
<td>75</td>
<td>29.3</td>
<td>33.4</td>
<td>11.8</td>
<td>26.3</td>
</tr>
<tr>
<td>ADR055</td>
<td>1.46</td>
<td>30</td>
<td>50</td>
<td>Failed</td>
<td>Failed</td>
<td>Failed</td>
<td>Failed</td>
</tr>
</tbody>
</table>

\(K_v = K_r = 10^6\) kN/m, \(\sigma_0 = 95\) MPa

1 Derived from SEM results

References