The response of stiffened square plates subjected to localised blast loading

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Abstract

An investigation has been conducted to examine the behaviour of square plates, with different stiffener configurations, to a central localised blast load. The plates were 126 mm square, 1.6 mm thick, with built-in boundary conditions. The aim of this work is to determine the dynamic response of stiffened square plates to localised blast loads, and to assess the effect of stiffener configuration on plate failure. The purpose of this paper is to present the results of the experiments and the numerical analyses. Experimentally, a localised impulsive load was created using plastic explosive, and the resulting impulse was measured using a ballistic pendulum. Configurations tested included unstiffened (flat plates), single and double stiffened plates. The plates exhibited mode I (large inelastic deformation) and mode II (thinning and/or capping) types of response. Numerical modelling using ABAQUS/Explicit was also performed. Temperature dependent material properties, as well as strain rate sensitivity, are included in the numerical modelling. Predicted values for mid-point deflections, overall deformed plate profiles and, where applicable, tearing locations are compared with experimental data. The numerical predictions, complimented by the experiments, give new insight into the effect of stiffener configuration on plate response to localised blast loads.
Introduction

The response of structural components subjected to blast loading has been the subject of a great deal of research. Much of this research has concentrated on the response of plates to impulsive loads, uniformly distributed over the whole of the plate area, as reported by Nurick and Martin [1,2]. The response of circular plates to a central localised blast load has been examined experimentally [3,4], theoretically [5] and numerically using ABAQUS/Explicit [6,7]. A fragment may be produced from plates subjected to localised impulsive loading, known as a cap. Wiehahn [6] included temperature dependent material properties in a numerical model of circular plates subjected to localised blast loading, and reported that "capping" failure of plates appeared to be the result of a thermo-mechanical instability.

Temperature dependent material properties have also been used in the numerical modelling of stiffened quadrangular plates subject to uniformly distributed impulsive loading by Chung Kim Yuen [8]. Square and rectangular plates with various stiffener configurations were investigated, experimentally and numerically. Little research appears to have been performed on the response of quadrangular plates to localised blast loads. The work is extended in this paper to examine the response of square plates to localised impulsive loading; the stiffener configurations are shown schematically in figure 1, and include unstiffened (flat), single (S) and double (D) stiffened plates.

Figure 1: Schematic of investigated stiffener configurations, showing the flat, single (S) and double (D) stiffened types, respectively.

Experimental method

The specimens were square plates, 220 by 220 mm; the test area was machined with a side length of 126 mm and a thickness of 1.6 mm. For the stiffened plates, the stiffener(s) and the plate were manufactured as a single unit in each case. The stiffeners for all plates were similar (3 mm wide and 7 mm in height). The S plates had one stiffener centrally located, while the D plates had two stiffeners symmetrically located. The plates were bolted onto a ballistic pendulum, to enable the measurement of blast impulse. Plastic explosive (PE4) was formed into 36 mm diameter disks and positioned at the centre of the plate, on top of a 12 mm thick polystyrene foam pad to attenuate the blast and prevent spallation.
Different thicknesses of explosive disk were used to vary the impulse applied to the test plate.

For each test, blast impulse, permanent displacement and the final deformed shape profile were measured. Lengths of material thinning or tearing were measured, and their locations on the plate were recorded.

**Numerical model**

Numerical analyses of selected plates were performed using ABAQUS/Explicit. The analyses incorporated non-linear geometry and material effects, strain rate sensitivity and temperature effects. Following Wiehahn [6] and Chung Kim Yuen [8], adiabatic analyses were performed due to the short response time of the plate, assuming that no significant heat conduction occurs between elements. A $\frac{1}{4}$ symmetry model, using C3D8R brick and C3D6 prism reduced integration elements, was constructed. A typical plate model, with the boundary conditions highlighted, is shown in figure 3.
The stress-strain curves obtained by Chung [8] from tensile tests were converted into true stress and logarithmic plastic strain, according to the ABAQUS/Explicit User Manual [9]. The temperature dependence of Young’s Modulus, \(E\), and yield stress, \(\sigma_y\), were reported by Masui et al. [10]:

\[
E = 210 \times 10^9 - 58.34 \times 10^6 \cdot T \quad \text{for} \quad T \leq 600 \, ^\circ\text{C} \\
E = 97 \times 10^9 + 3.1 \times 10^5 \cdot (T - 1100)^2 \quad \text{for} \quad 600 \, ^\circ\text{C} < T \geq 1100 \, ^\circ\text{C}
\]

\[
\sigma_y = \sigma_{yo} \quad \text{for} \quad T \leq 200 \, ^\circ\text{C} \\
\sigma_y = \sigma_{yo} \cdot [1 - 0.00178 \cdot (T - 200)] \quad \text{for} \quad 200 \, ^\circ\text{C} < T \geq 700 \, ^\circ\text{C} \\
\sigma_y = \sigma_{yo} \cdot [0.133 - 3.884 \times 10^{-4} \cdot (T - 700)] \quad \text{for} \quad 700 \, ^\circ\text{C} < T \geq 1000 \, ^\circ\text{C}
\]

Where: \(E\) = Young’s Modulus, \(T\) = temperature, \(\sigma_y\) = static yield stress, and \(\sigma_{yo}\) = static yield stress at the reference temperature of the tensile test.

Strain rate sensitivity was incorporated into the model using the well-known Cowper-Symonds relation, given in eq (3):

\[
\sigma'_y = \sigma_y \left( \frac{\dot{\varepsilon}}{D} - 1 \right)^{1/q}
\]

Values for material constants: \(\sigma_{yo} = 259 \text{ MPa}, D = 40.4 \text{ s}^{-1}, q = 5\).

The pressure loading from the explosive is related to the measured impulse, and is both a function of time and distance from the plate centre, as shown in eq (4). For simplicity, the pressure-time function is assumed to be a rectangular pulse, with an instantaneous rise time, peak pressure \(P_o\), and load duration \(\tau\); the load duration is assumed to be 2.25 \(\mu\)s, calculated from the burn time of the explosive.

\[
I = 2\pi \int \int r P(r, t) dr dt
\]

Where: \(I = \text{impulse}, r = \text{distance from plate centre}, t = \text{time}\)

From experiment, it was observed that an area larger than the explosive disk is discoloured by the blast, and is referred to as the ‘burn area’. Nurick and Radford [3] also reported a measure of discolouration on the loaded side of their explosively loaded plates, referred to as the burn diameter (not the heat area). As a first approximation of the loading distribution, the pressure is assumed to be constant over the burn area, and zero at all other locations on the plate. This distribution is described by eq (5) and shown schematically in figure 4. \(P_o\), the peak pressure, was calculated from the measured impulse using eq (4) and eq (5).

\[
P(r) = P_o \quad \text{for} \quad 0 \leq r \leq r_{\text{burn}} \\
P(r) = 0 \quad \text{for} \quad r_{\text{burn}} < r \leq \frac{1}{2}W
\]

Where: \(r_{\text{burn}} = \text{burn radius and} \frac{1}{2}W = \text{plate half side length}\)
Results and discussion

Blast tests

The unstiffened plates exhibited typical mode I response, with a single peak at the centre of the plate. The deformation takes the shape of a circular dome, moving out from the centre, transforming to a more quadrangular shape towards the support, as a result of the boundary conditions. Plastic hinges were observed, extending from the plate corner to the base of the deformed dome. Typical responses are shown in figure 5. Points of inflexion (where the deformation changes from a concave shape to a convex shape) were observed around the plate, and described by an inflexion radius, that is a radius from the plate centre where a marked change in the displacement gradient occurs. At higher impulses, thinning of a central cap occurs. For a particular test at an impulse of 12.5 Ns, two rings are visible, approximate radii of 10 mm and 21 mm respectively. The larger ring exhibited greater thinning, and its radius is similar to the inflexion radii recorded for tests at lower impulses.

Introducing a single stiffener significantly affects the plate response. Single stiffened (S) plates show a "double peak" in the permanently deformed profile, as shown in figure 6a, either side of the stiffener. Along the stiffener direction, the displacement profile resembles that of a mode I beam response. The double peaks are approximately symmetrical; one peak is slightly larger than the other, the difference being less than one plate thickness in all cases. The maximum displacements (from the double peaks either side of the stiffener) are approximately 2 plate thicknesses greater than the mid-point deflections.

The maximum displacements of the S plates are smaller than those for flat plates with similar applied impulses. However, tearing of the S plates occurs at lower impulses than for unstiffened plates. Thinning of the plate along either side of the stiffener is roughly symmetrical, although partial tearing of the plate tends to initiate on the side of the stiffener with the greater peak displacement. Due to the concentrated nature of the loading, at higher impulses the plate material tears away from the stiffener, creating two symmetric "petals". This effect is illustrated in figure 6c.

The double stiffened (D) plate response gave maximum displacements that, in most cases, lay in the range between the S and the flat plates. The maximum
deflections were at the mid-point of each double stiffened plate. The deformed shape profiles in the “along stiffener” direction were similar in shape to those for the unstiffened plates, but with lower magnitudes of peak displacement. Between the stiffeners, the points of inflexion fell along the circumference of a circle with diameters greater than the stiffener spacing. Once the “inflexion circle” circumference reached the stiffeners, the points of inflexion followed the line of the stiffener. It can be seen from figure 7 that most of the deformation is concentrated within this central zone.

The D plate material tore along the inside edges of both stiffeners, demonstrating good symmetry of loading and plate geometry. The stiffener spacing, initially 40mm, increased due to the stretching of the plate in the “across stiffener” direction (maximum stiffener spacing ranged from 43.2 to 48.5 mm). The central displacement and the localised bulging effect are more prominent at higher impulses. The amount of tearing along the stiffener also increases with increasing impulse, until the plate material in the central section tears and folds outwards (known as ‘petalling’), as shown in figure 7c.

(a) Impulse = 8.1 Ns  
(b) Impulse = 9.5 Ns  
(c) Impulse = 12.5 Ns

Figure 5: Typical response of flat plates, showing the overall shape (above) and the deflection profile (below)

(a) Impulse = 5.4 Ns  
(b) Impulse = 8.8 Ns  
(c) Impulse = 12.8 Ns

Figure 6: Typical response of single stiffened plates
Numerical model

The numerical analyses were performed without prior knowledge of the experimental results. As the measured experimental impulses were unknown, impulses of 5.7, 7.1, 8.7 and 9.5 Ns in magnitude were applied to most of the plates; these values are close to the experimentally measured impulses. Tests using higher impulses were simulated using the impulse values measured from the particular blast test in question. A burn diameter of 60 mm was also used, which is similar to burn diameters measured during the blast tests (although a high degree of scatter was noted and the measurement of burn diameter can be highly subjective). Figure 8 compares the experimental and the numerically obtained permanent mid-point displacements; there appears to be favourable agreement between prediction and experiment.

Figure 9 shows the temperature distribution and the permanently deformed profile of a flat plate subjected to an impulse of 9.5 Ns. Figure 9b shows a contour ‘ring’ of elevated temperature (circa 700°C), which corresponds to a ring of thinning visible on the displacement contour plot in figure 9a. This prediction of thinning of the plate around a radius of inflexion compares well with experiment; the photograph in figure 5b shows a radius of inflexion on the tested plate.

The behaviour of single stiffened plates is also predicted well. From figure 8, it can be seen that the FE predictions are very close to the test results. The double peaks either side of the stiffener are predicted by the FE results. Figure 10 shows the temperature and displacement profiles for a single stiffened plate subjected to an impulse of 8.7Ns. The predicted behaviour is similar to that found by experiment, shown in figure 6b. The maximum deflections are similar, and tearing occurs along the stiffener edge in both the numerical and experimental cases. Figure 11 shows the progression of tearing predicted by FE analysis, specified by T > 650°C; the FE results predicted a tearing length of 37mm, which compares well with the measured length of 40mm.
experimental case, tearing was initiated along one side of the stiffener only (possibly due to a slight asymmetry in the loading) and this cannot be modelled.

The double stiffened plate predictions also exhibit similar behaviour to that observed during experiment. Figure 12 shows the FE predictions for a double stiffened plate subjected to an impulse of 9.5 Ns (the corresponding blast test plate is shown in figure 7b). Most of the deformation is concentrated in the central region, with mid-point displacement predictions within 1 mm of the experimentally measured value of 26.8 mm. Tearing is initiated along the inside edge of the stiffener, indicated by the line of elevated temperature shown in figure 12b. However, the model appears to under-predict tearing lengths; this is most likely due to the idealisation of the loading.

Figure 8: Experimental and numerical results showing mid-point displacement against applied impulse

Figure 9: FE results showing contour plots of temperature and displacement for a flat plate subjected to an impulse of 9.5 Ns.
Figure 10: FE results showing temperature and displacement plots, at the point of tearing \((t = 102\mu s)\), for a single stiffened plate subjected to an impulse of 8.7 Ns.

(a) Temperature mid-way through thickness \((\text{max} = 678^\circ C)\)  
(b) Transverse displacement profile

Figure 11: FE temperature contour plots showing the progression of tearing for a single stiffened plate subjected to an impulse of 8.7 Ns.

(a) \(t = 165\mu s \) \((\text{max temp} = 706^\circ C)\)  
(b) \(t = 602\mu s \) \((\text{max temp} = 733^\circ C)\)

Figure 12: FE results showing contour plots of temperature and displacement for a double stiffened plate subjected to an impulse of 9.5 Ns.

(a) Permanent displacement \((\text{max} = 26mm)\)  
(b) Close-up of temperature plot \((\text{max} = 765^\circ C)\)
Conclusions

It can be seen that stiffener configuration has a significant effect on the overall plate response. A stiffener located along the mid-line of the plate significantly reduces the overall plate deformation, but the additional stiffness in this highly strained region leads to tearing, along the stiffener edge, at lower impulses. D plates have displacements that are between those observed for flat and S plates. The FE model appears to predict well the behaviour of the blast loaded plates due to the use of temperature dependant material properties and adiabatic analysis. An evident shortcoming of the model is the dependence of the load idealisation on the burn diameter. The exact nature of the load distribution is not well understood and this is an area currently under investigation [11].

References