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Deformation of thin plates subjected to impulsive load: Part III – an update 25 years on

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ABSTRACT

In 1989, Nurick and Martin published two review papers on the deformation of thin steel plates subjected to impulsive air-blast loading. The state of the art has progressed significantly in the following 25 years, and this review paper restricts itself to experimental studies that investigate the response of monolithic metal plates subjected to air-blast loading generated by detonating plastic explosive. From the large number of experiments reported, it is shown that the failure progressions in circular and quadrangular plates are similar and can be adequately described by three "failure modes" – namely large plastic deformation (mode I), tensile tearing (mode II) and shearing (mode III) although the severity and location of these failures on the plates is primarily determined by spatial distribution of the blast loading across the plate surface, and that boundary conditions significantly influence the onset of shearing and tearing failures due to variation in the in-plane movement of the plate material. The non-dimensional analysis approaches used by Nurick and Martin have been expanded to include the effects of load localisation and stand-off distance, and show good correlation with the expanded sets of test data published since 1989. It is concluded that these approaches still hold merit as simple tools for evaluating the likely effect of a close proximity air blast load on a flat metal plate.

1. Introduction

The study of structural response to impulsive blast loading has been performed for many years. In 1989, Nurick and Martin [1,2] reviewed data from previous experimental and theoretical investigations into the response of flat, monolithic metal plates subjected to blast loading. In addition, new experimental data were reported and non-dimensional analysis was utilised with the aim of developing a simple, empirical prediction of the displacement of a blast loaded plate with fully clamped boundary condition [2]. Since 1989, there have been many experimental, analytical and numerical modelling investigations into the response of structures to blast loading. These have expanded the types of structures examined to include different plate geometries, stiffened and welded structures, sandwich panels, composite materials and monolithic metal plates with different boundary conditions. Tensile tearing and shear failures have also been investigated alongside large plastic deformation responses. Different forms of loading, including localised loading and stand-off distance effects have also been studied.

This paper reviews the literature that have been published since 1989 in an attempt to update the work presented by Nurick and Martin [1,2]. Using the post 1989 developments in non-dimensional analysis, much of the more recent experimental data are then translated into non-dimensional impulse and displacement parameters and plotted alongside the data presented in Ref. [2] to determine if the empirical relationships proposed in 1989 are still valid. Due to the myriad of papers in this area, this review paper restricts itself to experimental studies that investigate the response of monolithic metal plates subjected to air-blast loading generated by detonating plastic explosive. Unless otherwise stated, the reviewed results are concerned with flat mild steel plates.

2. Experimental studies since 1989

In order to summarise the experimental work performed in the past twenty five years, the studies presented in the literature are summarised in Table 1 according to the following classifications:

- loading type: uniform, localised, varying stand-off distance;
- plate geometry: circular or quadrangular; stiffened or flat;
- boundary conditions; and
- failure mode: large plastic deformation, tensile tearing, shear failure.

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Nomenclature

B	plate width
I	impulse
L	plate length
R	exposed plate radius
R_o	charge radius
S	stand-off distance
t	plate thickness
W	TNT equivalent mass
Z	Hopkinson scaled distance
δ	permanent mid-point displacement
ϕ_c	non-dimensional impulse for circular plates
ϕ_{cS}	non-dimensional impulse for circular plates, incorporating stand-off distance
ϕ_q	non-dimensional impulse for quadrangular plates
ρ	material density
σ	characteristic stress = quasi-static yield stress

2.1. Uniform loading conditions

Teeling-Smith and Nurick [3] investigated the progression in failure of clamped circular plates subjected to uniform blast loading. Photographs of plate failures at different impulses are shown in Fig. 1. At low impulse levels, large plastic deformation (known as Mode I failure) was observed, with mid-point displacement increasing with increasing impulse. As impulse was increased, thinning occurred at the plate boundary (known as Mode Ia or Mode Ib, depending upon the proportion of the circumference that exhibited necking), which was a precursor to tensile tearing along the boundary edge [3]. As impulse reached a threshold value, partial tearing (known as Mode II*) of the plate edge occurred. This Mode II* failure is the transition between Mode I and Mode II (tensile tearing of the boundary edge) failure. As impulse increased further, plates exhibited tensile tearing of the boundary edge. If the impulse was increased beyond the threshold required for complete boundary tearing, the mid-point displacement of the plates decreased with increasing impulse and the failure mode tended towards transverse boundary shear (known as Mode III) [3]. The observed failure modes were similar to those reported by Menkes and Opat [30] for explosively loaded beams and the definitions of the failure modes are summarised in Table 2 for blast-loaded plates.

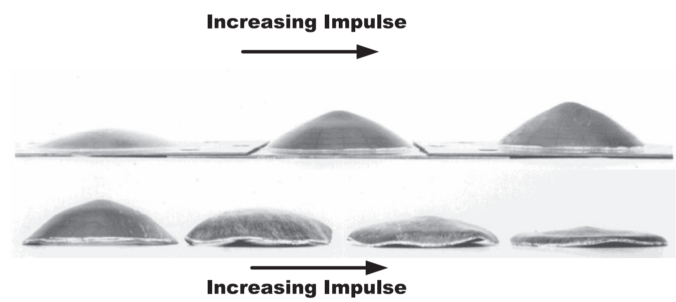

Fig. 1. Photographs showing the failure of uniformly loaded circular plates with increasing impulse [3].

Nurick and co-workers [4,5] investigated the influence of boundary conditions on the failure of uniformly loaded circular plates in follow-on studies from the work reported in Ref. [3]. Thomas and Nurick [4] compared the fully clamped and built-in boundary conditions and showed that the boundary condition has little influence upon plate response during Mode I (large plastic deformation) failures. However, the onset of boundary thinning and subsequently boundary tearing were significantly influenced by the type of boundary condition. The built-in plates exhibited the onset of thinning and tearing at lower impulses since the boundary was more rigid and the clamped boundary was unable to fully prevent in-plane

Table 1
Summary of experiments performed since 1989 on air-blast loaded metal plates.

Load type	Plate type[1]	Reference	Notes	Nominal plate dimensions (mm)	Year
Uniform	C	Teeling-Smith and Nurick [3]	Failure Modes I, II and III of circular plates	∅ 500–1000 × 10–20	1991
		Thomas and Nurick [4]	Built-in versus clamped boundaries	∅ 100 × 1.6	1995
		Nurick et al. [5]	Influence of edge sharpness: clamped plates	∅ 60–120 × 1.6	1996
		Cloete et al. [6]	Annular and centrally support plates, failure	∅ 100 × 1.6	2005
	Q	Olson et al. [7]	Failure progression, tearing initiation	89 × 89 × 1.6	1993
		Nurick and Shave [8]	Failure progression, tearing initiation	89 × 89 × 1.6	1996
		Bonorchis and Nurick [9]	Varied boundary conditions	188–200 × 108–120 × 3	2007
Localised	C	Wierzbicki and Nurick [10]	Failure modes	∅ 100 × 1.6	1996
		Nurick and Radford [11]	Failure modes, capping	∅ 100 × 1.6	1997
		Chung Kim Yuen and Nurick [12]	Influence of plate thickness, load-to-plate diameter ratio	∅ 100 × 1.6–3.6	2000
	Q	Jacob et al. [13]	Varied load and plate geometries	160–290 × 160–290 × 1.6–4.0 (different aspect ratios)	2004
		Langdon et al. [14]	Flat and stiffened plates	126 × 126 × 1.6	2005
Stand-off distance	C	Jacob et al. [15]	Influence of stand-off distance on Mode I failure, use of tube to direct blast	∅ 106 × 1.9	2007
		Yao et al. [16]	Mild steel, 12.9–17.6 mm stand-off distance, dimensionless analysis	160 × 160 × 1.6–4.0	2015
		Neuberger et al. [17]	Scaling	∅ 100 × 1.6	2007
		Neuberger et al. [18]	Springback of armour steel	∅ 1000 × 20	2009
	Q	Jacinto et al. [19]	Boundary conditions, model validation	950–1000 × 950–1500 × 0.9–2.1	2001
		Yuen et al. [20,21]	Large scale field tests, scaling	500 × 500 × 3–6	2006
Uniform	QS	Schubak et al. [22–25]	One and two way stiffeners, model validation	4000–4572 × 2438–4000 × 6–7	1992–1993
		Nurick et al. [26]	Influence of integral stiffeners	89 × 89 × 1.6	1995
		Schleyer et al. [27]	Effects of loading direction, in-plane restraint on pulse loaded welded stiffened plates	1000 × 1000 × 2	2003
		Yuen and Nurick [28]	Influence of integral stiffeners	126 × 126 × 1.6	2005
		Veldman [29]	Riveted stiffened plates, pre-pressurisation	508 × 610 × 1.6	2008

[1] C = circular, Q = quadrangular, QS = quadrangular stiffened.

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