International Journal of Mechanical Sciences 65 (2012) 177–191

Contents lists available at SciVerse ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

The dynamic performance of simply-supported rigid-plastic circular steel plates subjected to localised blast loading

K. Micallef [a], A.S. Fallah [a,*], D.J. Pope [b], L.A. Louca [a]

[a] Department of Civil Engineering, Imperial College London, London SW7 2AZ, UK
[b] Physical Sciences Research Department, D.S.T.L., Porton Down, Salisbury, Wiltshire, SP4 0JQ, UK

ARTICLE INFO

Article history:
Received 12 November 2011
Received in revised form
5 September 2012
Accepted 6 October 2012
Available online 17 October 2012

Keywords:
Rigid plasticity
Circular plate
Localised blast loading
Plasticity bound theorems
Pulse-shape dependence

ABSTRACT

Near-field explosive charges, such as buried land mines, produce localised blast loadings which can potentially cause damage to property and/or loss of life in both military and civil structures. As the localised short duration blast pulse affects most severely a small area of a plated structure, boundary effects are not as significant as they are when a quasi-static or global blast loading is applied and full plate action may not be utilised.

Many common structural forms are composed of individual plated elements and thus the investigation of localised blast loading effects on plates is a prerequisite to understanding the integral behaviour. Typically, plates are made of ductile materials such as steel, which exhibit considerable post-yield deformation capacity when subjected to such extreme dynamic loads. Analytical study of the dynamic plastic response of rigid-plastic plated structures is the aim of the present study.

A circular plate is studied in the present work and a general form of a localised blast loading function with a spatial variation having a central radial zone with constant pressure and exponentially decaying profile outside the zone is assumed. Assuming that steel exhibits perfectly plastic behaviour and ignoring membrane action, transverse shear and rotatory inertia effects, the static plastic collapse pressure is initially found and the analysis is extended to take into account the inertial effects arising from dynamic loading. Results for the permanent transverse displacements are found for rectangular and linearly and exponentially decaying pulse loads.

For high loads and/or loads of short duration, it was found that the permanent transverse displacement can be found by replacing the applied pulse load by means of an impulsive velocity without great loss of accuracy. Good correlation with numerical simulations obtained from ABAQUS/Explicit is achieved (within 15% accuracy) for plate geometries falling within the identified limits where membrane and shear effects are negligible.

The predicted final transverse displacements are found to be dependent on the loading pulse shape, but the pulse-shape effects are eliminated by using the correlation parameters (effective impulse and pressure) advocated by Youngdahl (1971) [52] to give a single pulse shape-independent curve for the final plate deflection as a function of the effective pressure and effective impulse.

1. Introduction

Most ductile engineering materials, such as steel, have considerable reserve strength beyond their yield point and such strength may be used in practical applications to realistically estimate the capacity up to failure when such a material is subjected to dynamic load. Thus, it is meaningful to investigate the behaviour of structures which are subjected to a load of sufficient intensity such that plastic deformation occurs.

In such an analysis, it is desirable to idealise the material behaviour as being elastic-perfectly plastic or rigid-perfectly plastic. Thus, the material is rigid whenever the stress is less than the uni-axial yield stress value, σ_0.

Such a simplification permits the study of the main characteristics of structures with relative simplicity and without great loss of accuracy. In fact, the collapse loads predicted by such simplified methods often show good correlation with experimental data, as seen in Sections 1.1 and 1.2.

In most engineering applications, structural elements can be geometrically classified as being either beams or plates. Beams are members whose lengths are large when compared to their cross-sectional sizes and whilst idealisation of frame structures into beam elements is justified, many engineering structures can be more readily idealised as being composed of plates.

In fact, the performance of plated steel has been the subject of a number of studies which have been carried out in the past.

* Corresponding author. Tel.: +44 20 7594 6028; fax: +44 20 7594 5934.
E-mail address: as3@imperial.ac.uk (A.S. Fallah).

0020-7403/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmecsci.2012.10.001

Nomenclature

Latin lower case

a	loading parameter [1]
b	loading parameter [L^{-1}]
p_0	maximum overpressure, [$M L^{-1} T^{-2}$]
$p_1(r)$	spatial part of pressure pulse load, [$M L^{-1} T^{-2}$]
$p_2(t)$	temporal part of pressure pulse load, [$M L^{-1} T^{-2}$]
p_c	static collapse pressure, [$M L^{-1} T^{-2}$]
p_e	Youngdahl's effective pressure, [$M L^{-1} T^{-2}$]
p_l	lower bound static collapse pressure, [$M L^{-1} T^{-2}$]
p_u	upper bound static collapse pressure, [$M L^{-1} T^{-2}$]
r	radial axis direction, [L]
t_{mean}	Youngdahl's mean time, [T]
w_f	final plate transverse displacement, [L]
w_i	plate transverse displacement at the ith phase, [L]
$\dot{w}_i$	plate transverse velocity at the ith phase, [$L T^{-1}$]
$\ddot{w}_i$	plate acceleration at the ith phase, [$L T^{-2}$]

Latin upper case

$A_i - H_i$	integration constants [various]
$\dot{D}$	internal energy dissipation rate, [$M L^2 T^{-3}$]
$\dot{E}$	external energy dissipation rate, [$M L^2 T^{-3}$]
I	impulse per unit surface area, [$M L^{-1} T^{-1}$]
I_e	Youngdahl's effective impulse, [$M L T^{-1}$]
M_0	plastic collapse moment per unit width, [$M L T^{-2}$]
M_r	radial bending moment per unit width, [$M L T^{-2}$]
M_θ	circumferential bending moment per unit width, [$M L T^{-2}$]
Q_r	lateral shear force per unit width, [$M T^{-2}$]
R_0	radius of central uniformly-loaded region, [$M L T^{-2}$]
R	plate radius, [L]
V_0	initial impulsive velocity, [$L T^{-1}$]
W_f	final maximum plate transverse displacement, [L]
W_i	maximum plate transverse displacement at the ith phase, [L]
$\dot{W}_i$	maximum plate transverse velocity at the ith phase, [$L T^{-1}$]
$\ddot{W}_i$	maximum plate acceleration at the ith phase, [$L T^{-2}$]
X	load parameter [1]
Y	load parameter [1]

Greek lower case

α	plate parameter [L^3]
β	plate parameter [L^3]
γ	plate parameter [1]
δ	plate parameter [L^2]
ε	plate parameter [L^3]
η	dynamic load factor [1]
η_{crit}	critical dynamic load factor [1]
η_e	effective dynamic load factor [1]
κ_r	radial curvature [1]
κ_θ	circumferential curvature [L^{-1}]
$\dot{\kappa}_r$	change of radial curvature, [T^{-1}]
$\dot{\kappa}_\theta$	change of circumferential curvature, [$L^{-1} T^{-1}$]
μ	plate mass per unit area, [$M L^{-2}$]
λ	dimensionless kinetic energy [1]
ξ	plastic hinge position [L]
$\dot{\xi}$	travelling plastic hinge velocity, [$L T^{-1}$]
ξ_0	initial plastic hinge position [L]
τ	pulse load duration [T]
φ	load parameter [1]
ω	loaded area ratio [1]

1.1. Static plastic behaviour of plates

The first study of the static behaviour of steel plates was done by Hopkins and Prager [1] in 1953, who found the static collapse pressures for perfectly plastic circular plates of various support conditions and subjected to various cases of symmetrical loading, viz., a central concentrated load, annular loading, circular loading and uniform loading.

Onat and Haythorntwaite [2] and Hooke and Rawlings [3] later confirmed the theoretical results, although it was found that the predictions were only valid for transverse displacements equal to about a half of the associated plate thickness.

However, a number of engineering applications involve plated structures being subjected to extreme loads which are well beyond the elastic limit of materials.

Blast is one such extreme load and steel has traditionally been the most widely used materials in the field of protective structures and is still the dominating material in the field [4].

A very comprehensive review of blast loading on plates was prepared by Rajendran [5], which also includes descriptions of blast detonation and shock wave propagation, wave-plate interaction and response of plates to various forms of blast loading.

With respect to steel plates, considerable studies have been carried out on the plastic behaviour of such plates of various geometries and support conditions.

1.2. Dynamic plastic behaviour of plates

The first dynamic study was done by Wang and Hopkins [6] in 1954, who studied clamped circular plates subjected to a uniformly distributed ideal impulse. Many similar studies were subsequently conducted by various authors who all studied the performance of plates under blast and/or impulsive loading for different boundary and loading conditions.

Hopkins and Prager [7] carried out a similar study to [6] but for a simply supported plate.

Shapiro [8] studied the dynamic behaviour of an annular plate which is clamped around the inner edge and free on the outer edge, with the latter subjected to a constant axi-symmetric velocity which is removed suddenly.

Wierzbicki and Florence [9,10] investigated clamped steel plates and considered strain-rate effects.

Florence [11] studied a similar problem but with the outer edge subjected to a transverse impulse rather than a constant velocity. Florence [12] later generalised the work of Wang and Hopkins for any arbitrary uniform loading but only for the case of a rectangular pulse and later [13,14] studied the response of a clamped plate subjected to a centrally located uniform load. Conroy [15] examined the same problem but for a plate with simply supported supports.

An annular plate which is simply supported at the boundary, free at the inner edge and subjected to an axi-symmetric impulsive velocity varying linearly from a maximum at the inner