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The response of mild steel and armour steel plates to localised air-blast loading-comparison of numerical modelling techniques

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ABSTRACT

This paper presents a comparative study of numerical, experimental and empirical techniques on the effect of localised air blast loads on mild steel and armour steel plates. The blast load effects on monolithic plates have been accounted for by using different approaches provided in the Finite Element hydrocode ABAQUS 6.13, namely an Eulerian Lagrangian and a Coupled Eulerian Lagrangian model. In the first model, the air and the explosive were modelled using multi-material Eulerian grids while the plate was modelled using a rigid Lagrangian mesh, while in the second model the rigid target was replaced with deformable plate.

The transient deformation of the plate, strain localisation, pressure distribution on the plate have been investigated in the FE models, which have been validated against small scale experimental data for a limited range of charge sizes for both the mild steel and armoured steel. Despite the lower deflection of armour steel compared to mild steel plates, both plates were shown to undergo rupture upon similar charge mass and stand-off. For this purpose, a non-dimensional analysis was carried out with consideration of stand-off distance and slenderness ratio to predict the rupture impulse.

1. Introduction

Events such as 9/11 and the recent European bombings (2015–2017) have caused public awareness of explosive threats to increase dramatically. In response to the risk of explosions, efforts have been made to improve the response of civil structures and transportation vehicles to air-blast loading. It is important to understand the loading arising from an explosive detonation and the resulting damage sustained by nearby structures. Careful materials selection can greatly assist in providing much needed blast protection for vulnerable structures, with high strength armour steels (which have been excellent in ballistic applications) being an obvious potential candidate. Such steels provide much higher strengths and hardness (which are good for resisting projectile penetration) but at the expense of reduced ductility [1–3].

A blast wave is generated by a rapid release of energy which propagates through a medium. Whether the type of blast is localised, for example, buried land mines, or globalised (far field explosions), the structure may respond in different ways: either deflecting some of the blast wave, or undergoing large inelastic deformation, partial or complete tearing and shear failure. Subject to uniform pressure load, the plate elements may respond in different local modes of failure. These failure modes were initially classified by Menkes and Opat [4] for beams but later developed by Nurick and Radford [5], and Olson et al. [6] for plates. These comprised of Mode I-large inelastic deformation, Mode II-large inelastic deformation with tensile tearing at supports and Mode III-transverse shear failure at supports. Jacob et al. [7] report similar observations for locally blast loaded plates which included the large inelastic displacement at the centre (mode I), partial tearing at central area (IIc*) and capping or complete tearing at centre (IIc). The locally loaded plate profile is governed by a smaller dome atop a larger dome.

Nurick et al. [8–15] have reported considerable experimental data on the response of steel plates to air-blast loading during the past 25 years. Spatial loading distribution (localised versus uniform), explosive mass and shape, boundary conditions, plate size and shape and plate thickness were varied. A non-dimensional impulse parameter, originally proposed in 1989 [10] and subsequently modified [16] to incorporate changes to loading conditions and plate geometries, has been used to collapse the data to a single trend-line which allowed for the prediction of permanent mid-point displacement [9]. A recent review paper by Chung Kim Yuen et al. [8] reviewed the abundance of mild

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Nomenclature

Latin upper case

A_0	burn area, $[L^2]$
B	plate breadth, [L]
C_p	ideal gas specific heat at constant pressure, $[L^2T^{-2}K^{-1}]$
C_v	ideal gas specific heat at constant volume, $[L^2T^{-2}K^{-1}]$
D_e	load diameter [L]
H	thickness of the plate, [L]
I^*	non-dimensional impulse [1]
$\hat{I}$	impulse density, $[ML^{-1}T^{-1}]$
L	plate length, [L]
M_0	maximum moment per unit length, $[MLT^{-2}]$
S_D	stand-off distance, [L]
R_b	burn radius, [L]
V_0	initial impulsive velocity, $[LT^{-1}]$
W	plate maximum displacement at centre, [L]
Z	Hopkinson's scaled distance, $[LM^{-1}]$

Latin lower case

a	explosive constant [1]
b	explosive decay constant, $[L^{-1}]$
m	mass of explosive [M]
r_e	radius of disk explosive, [L]
h_e	charge height, [L]
p_0	maximum explosive pressure, $[ML^{-1}T^{-2}]$
$\dot{w}$	plate velocity, $[LT^{-1}]$
p_c	static plastic collapse pressure, $[ML^{-1}T^{-2}]$

Greek lower case

δ, w_f	plate permanent deflection, [L]
$\hat{\theta}$	homologous temperature, [K]
$\dot{\varepsilon}$	material strain rate, $[T^{-1}]$
ρ	material density, $[ML^{-3}]$
τ	positive duration of the blast load, [T]
μ_0	dynamic viscosity, $[ML^{-1}T^{-1}]$
μ	areal density, $[ML^{-2}]$
γ	plate width/length ratio, [1]
$\varnothing_{ql}$	modified normalised(dimensionless) impulse, [1]
$\varnothing_{sl}$, $\varnothing_{sl'}$	modified normalised impulse with stand -off effects [1]
σ_0	material static yield stress, $[ML^{-1}T^{-2}]$
σ'_y	material dynamic yield stress, $[ML^{-1}T^{-2}]$
σ_{UT}	ultimate tensile stress, $[ML^{-1}T^{-2}]$
λ	dimensionless kinetic energy, [1]
γ'_s, γ_{SL}	dimensionless load parameters, [1]
ω	natural frequency of vibration $[T^{-1}]$

steel test data and fitted it all to one trend-line, confirming the trends predicted by Nurick and Martin in 1989 [10].

Neuberger et al. [17,18] conducted experimental studies on the Rolled Homogeneous Armour (RHA) steel subject to air blast and buried charge loading from spherical TNT charges. The deformation combs such as used by Neuberger [18] provides information about the maximum transient displacement of a plate (usually at the mid-point) but cannot give details regarding the time to peak of the deformation profile across the plate. There is also the possibility of contact measurement techniques influencing the response of the plates, a drawback that can be overcome by using non-contact measurement techniques such as high speed imaging.

Fourney et al. [19] and Spranghers et al. [20] used high speed photography and 3D Digital Image Correlation (DIC) to measure the transient response of plates subjected to low charge mass explosive detonations. Small apertures on the lenses were used by Spranghers et al. [20] to ensure sufficient depth of field for tracking the plate motion, and challenges of changing light conditions on the specimen as it moved. Aune et al. [21] used high speed photography to film the motion of a blast loaded plate mounted in a stationary rigid clamp frame. The cameras were placed in the same room at the blast event and Aune et al. [21] reported that the blast wave reduced the accuracy of data capture after the blast wave had impinged on the cameras. However, in a later numerical study, Aune et al. [22] concluded that the DIC technique was capable of capturing the deflection histories throughout the entire test as long as the movement of the mounting frame was accounted for in the calculations.

Much of the past work on blast loaded plates has concentrated on relatively ductile steels, which exhibit large plastic deformations and then ductile tensile tearing at high charge masses. More recently, there has been interest in high strength steels, such as the ARMOX armour steels. Langdon et al. [1] reported the results of localised blast tests on mild steel, ARMOX 370T, aluminium alloy and fibre reinforced polymer composite plates. Permanent mid-point displacement increased linearly with increasing impulse for each material type, up to rupture. At higher charge masses, the mild steel plates exhibited ductile tensile rupture, while the armour steel plates (which ruptured at the same impulse) exhibited a more brittle type of failure. Non-dimensional impulse at rupture was observed to increase with increasing specific energy to tensile fracture (which was obtained by directly integrating the stress-strain curve obtained from uniaxial quasi-static tensile tests) [1].

Measuring the transient deformation history of plates (prior to failure) provides valuable information that improves our understanding of the mechanisms which influence and control the deformation and rupture of plates. This is particularly useful in high strength armour steels where the elastic energy stored during deformation is relatively high, as a proportion of the total deformation energy, compared to mild steel. On the other hand, armour steels have limited ductility compared to mild steel plates which dissipate energy in plastic strain.

Early work on the Fluid Structure Interaction (FSI) by Taylor [23] showed that as the limiting case of a plate with infinite mass is approached, the plate hardly moves and all of the incident pressure is reflected off the plate. Consequently, the impulse imparted to the plate reaches its maximum. In the case of thin plates, however, the plate equilibrates quickly and accelerates which relieves the reflected pressure, thus reducing the impulse. The theoretical work on the FSI effects by Taylor was extended to account for the fluid nonlinear compressibility effects which evaluated the transmitted impulse in terms of a single dimensionless parameter [24,25].

Advancements in numerical simulations have made it possible to observe the blast wave effects and its interactions with structures, using a Multi Material Eulerian approach. This approach incorporates the governing physics of FSI and was studied by Chen and co-workers [3,26–28]. Børvik et al. [27] observed a significant difference between the transient profiles of box containers due to the difference in the numerical techniques when modelling the pressure time history, despite the same total impulse.

With this rationale, this paper seeks to compare various ways of modelling the blast loading and response of high strength steel plates using the commercially available modelling package ABAQUS/Explicit. A new series of experiments supplements the data reported by Langdon et al. [1] on blast response of armour steels. Both sets of data are used to assist with model validation and comparing the various modelling approaches. Given the high strength steels have considerably higher yield stresses than ductile mild steels, the transient response is considered to be of great importance.