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Experimental response of high strength steels to localised blast loading

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ABSTRACT

Modern high-strength and armour grade steels have developed continually increasing strength and fracture toughness, but there have been limited experimental investigations into their response to localised blast response. In this work, the response of four modern steels to localised blast loading is experimentally investigated. The deformation and rupture threshold is comprehensively characterised and a detailed fractographic investigation is conducted into the initiation and progression of rupture failure modes. It was found that for the current experimental setup, higher strength steels can outperform more ductile steels, and that steel with a tailored microstructure had a higher rupture threshold than three modern armour steels. All steels studied herein initiate rupture via ductile shear fracture, as opposed to tensile tearing which is common in lower-strength steels. Results showed that the deformation resistance cannot be predicted precisely using only yield strength, and only by considering strain hardening can the deflection response be more accurately predicted. A new non-dimensional impulse correction parameter was also developed that captures the effect of charge stand-off on the target plate deformation and rupture performance. The results demonstrate the suitability of high-strength steels for blast applications, and have application to the design and analysis of safer armour systems for blast protection.

1. Introduction

Numerous military standards specify the selection criteria for various grades of steel intended for use in blast protection systems. These standards are traditionally based on the steel hardness and Charpy fracture toughness [1–3]. Across the standards, the materials intended for protection against blast loading are restricted to the lowest range of hardness (between 260 HB and 310 HB) and the most demanding minimum Charpy fracture toughness requirement (between 40 J and 76 J) of any grade of armour steel. This emphasis on ductility and toughness outlined in the standards is intended to limit the risk of material rupture under blast loading, particularly in the presence of stress concentrations [4]. The origins of these selection criteria date back to World War II and have remained essentially unchanged since [5]. With numerous developments in steel production techniques and tailored metallurgy, modern steels can be produced with ever-increasing combinations of strength and fracture toughness [6]. However, the appropriateness of these modern steel grades for blast protection is not effectively captured in the current material specifications due to the restrictions placed on material hardness. There is minimal experimental data currently available in the open literature on the localised blast response of modern high-strength and armour grade steels [5–7]. This includes lack of knowledge on the deformation response, the rupture threshold, and the progression of damage modes in rupture. This limits our understanding of their fracture behaviour and confidence in their use for blast protection.

Langdon et al. [7] examined the response of five materials to localised blast loading including two grades of mild steel and Armox 370T armour grade steel. The yield strength (σ_y) of the mild steel ranged from 250 MPa to 330 MPa and was 1150 MPa for Armox 370T. The specific energy to tensile fracture (SETF) of each material, calculated by integrating the uniaxial engineering stress vs. strain curve was used to characterise the energy absorption capacity and was compared to the charge mass rupture threshold at a fixed stand-off distance and charge diameter. A comparison of all materials accounting for target plate properties and loading conditions with a non-dimensional impulse parameter (NDIP) identified a monotonically increasing relationship between the SETF and NDIP at fracture. Interestingly the armour steel was observed to fracture under identical loading conditions as the mild steel irrespective of having a SETF that is less than half of the more ductile mild steel. Their investigation highlights the advantages of using armour steel over mild steel, as the rupture threshold is identical

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but the armour steel reduces the plate deformation by 45%. Latourte et al. [8] also observed the potential benefits of higher strength steels through their experimental evaluation of the response of different steels to high impulse under-water shock tube loading. Regardless of their similar SETF, they found that BA-160 (σ_y = 1100 MPa) remained intact when subjected to an impulse that was 70% higher than the lower strength TRIP-120 (σ_y = 830 MPa). However, these previous investigations provide only a limited insight into the range of high-strength and armour grade steels available, and there is a lack of understanding of how the material property variations within this class of materials affect the blast response.

The failure modes of structural steel subjected to localised blast loading have been extensively studied. Nurick and Radford [9] compared the failure modes of mild steel plates subjected to localised blast loading to the failure modes identified for uniform loading [10,11]. The deformation profile produced by localised blast loading was found to exhibit a central bulge super-imposed onto the global plate deformation. The inflexion point between the global and localised bulge was found to be proportional to the diameter of the explosive charge used in the experiments. With increasing magnitudes of blast loading, thinning of the plate in a narrow band is observed at the circumference of the central bulge. The localisation of material flow at this location due to tensile instability subsequently leads to tensile tearing of the plate and the release of a circular fragment. This failure mode is commonly referred to as capping. Further increases in blast loading result in the initiation of radial cracks from the existing fracture surface producing several petals of material which curl back as the cracks continue to propagate. Whilst Langdon et al. [7] observed that mild steel exhibited a large thickness reduction around the fracture location and a fibrous surface appearance suggestive of tensile tearing, they only observed a minimal thickness reduction for the Armox 370T armour steel. This combined with the illustrious and smooth fracture surface on the armour steel was suggestive of a brittle cracking failure mode [7], indicating that the failure modes of higher strength armour steels may differ from structural steels. This is supported by Bammann [12] who studied the deformation and fracture of HY-100 and HY-130 steels (σ_y = 690 MPa and 900 MPa, respectively) under localised blast loading. Numerical simulations of their blast experiments revealed that the plate failed under a shear fracture mode caused by narrow bands of high temperature material developing within the thinned section of the plate rather than by the tensile tearing mechanism commonly seen in structural steels. However, a comprehensive experimental characterisation of this potential shear failure mechanism, including detailed fractographic study, has not been conducted, and the initiation and progression of this mechanism and interaction with tensile fracture is not understood.

A non-dimensional impulse parameter (NDIP) for predicting maximum permanent deflection of a target plate under blast loading was originally presented by Nurick and Martin [13], and has been developed extensively by numerous researchers [11,14,15]. The impulse applied to the target plate by the blast loading is scaled by several parameters accounting for target plate dimensions, material properties and the dimensions of the explosive charge. For an extensive range of experimental programs a linear trend has been observed between the NDIP and the non-dimensional deflection [16,17]. An empirical fit to this relationship is produced, allowing the prediction of other load cases with a high degree of accuracy. However, for free air blast, this parameter does not account for the effect of stand-off distance which is a critical aspect for the magnitude and spatial distribution of localised blast loading experienced by a target plate.

This investigation presents significant new insights and knowledge for the response of high strength steels to localised blast loading. An extensive experimental investigation into the deformation and rupture was conducted, where Section 2 summarises and compares the four materials selected, and Sections 3 and 4 summarise the experimental blast test setup and results. Section 5 analyses the deformation response, and a new analytical parameter is developed (Section 5.2) that incorporates charge stand-off distance and is comprehensively evaluated using test results in this study and from published literature. This section also includes a comparison of the deformation performance of the four materials (Section 5.3), where new experimental and analytical insight is presented on the correlation between deformation resistance and material properties. Section 6 presents results for rupture threshold, and the new analytical parameter is applied to incorporate stand-off distance into the analysis of rupture for the first time. Finally, Section 7 presents a detailed fractographic study of fracture mechanisms in their initiation and progression, which definitively and experimentally characterises the shear failure mechanism and illustrates the interaction with tensile fracture in contributing to plate rupture.

2. Candidate materials

Four grades of high-strength steel with a minimum hardness of 350 HB were selected for blast testing. This level of hardness places all materials outside the specifications given for class 2 rolled homogenous armour steel that is intended for use in blast protection [1–3]. The candidate steels were selected with varying combinations of material strength and ductility as a means of exploring the influence of each property on blast performance. Three of the candidate materials are produced as armour-grade steels for use in protective structures. These quenched and tempered martensitic grades of steel are designed to US military specifications for three classes of armour steel and are labelled accordingly. The grades chosen are: 1) class 1 rolled homogeneous armour (RHA) [2]; 2) class 4a improved rolled homogeneous armour (IRHA) [2]) and; 3) high hardness amour (HHA) [18].

The fourth candidate material labelled ARS is a high strength abrasive resistant steel designed primarily for use in the mining and processing industries. Whilst this material is not certified under any armour steel specification, its unique metallurgy and high mechanical properties makes it an interesting candidate for use in protective structures. The ARS material is produced with a mixed microstructure of bainite, martensite and retained austenite. Under plastic deformation, the ARS material is strengthened by a transformation induced plasticity (TRIP) mechanism as the meta-stable austenite in the microstructure is transformed to martensite. This mechanism has been shown to increase the strain hardening capacity and will therefore delay tensile instability [19]. Preliminary characterisation was performed for each material by McDonald [20] with cylindrical tensile samples fabricated from a 10–15 mm plate. The quasi-static, uniaxial tensile response is shown in Fig. 1 and the key mechanical properties of each candidate are provided in Table 1. SETF is given by integrating the stress-strain curves up to the fracture strain and the hardening modulus is given by the gradient of the curves between the yield and ultimate tensile strength.

Comparing the candidate materials under tensile loading in Fig. 1, varying degrees of strength and ductility are clear. Whilst the RHA has a high yield strength and good ductility, its hardening modulus is significantly lower than the other materials with only a 9% increase in stress from its yield to its ultimate tensile strength (UTS). By contrast the IRHA, which has a slightly lower yield strength than the RHA displays a 41% increase in stress from yield to ultimate tensile strength. Given the large plastic strains experienced by target plates, the strain hardening behaviour of each material is an important aspect in the deformation resistance under blast loading. The HHA, which is generally integrated into ballistic armour packages, is not intended for use in blast protection and should be used with care in structural applications [4]. However, stress-strain relationship of the HHA shows that its high yield strength and hardening modulus coupled with reasonable ductility produces the highest SETF of any material in this study. The ARS shows good strain hardening and the largest uniform ductility (strain to UTS) of any material, reflecting the effects of TRIP strengthening. The effect of this property on blast performance of ARS will be