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Design and identification of high performance steel alloys for structures subjected to underwater impulsive loading

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ABSTRACT

Martensitic and austenitic steel alloys were designed to optimize the performance of structures subjected to impulsive loads. The deformation and fracture characteristics of the designed steel alloys were investigated experimentally and computationally. The experiments were based on an instrumented fluid–structure interaction apparatus, in which deflection profiles are recorded using a shadow Moiré technique combined with high speed imaging. Fractographic analysis and post-mortem thickness reduction measurements were also conducted in order to identify deformation and fracture modes. The computational study was based on a modified Gurson damage model able to accurately describe ductile failure under various loading paths. The model was calibrated for two high performance martensitic steels (HSLA-100 and BA-160) and an austenitic steel (TRIP-120). The martensitic steel (BA-160) was designed to maximize strength and fracture toughness while the austenitic steel (TRIP-120) was designed to maximize uniform ductility, in other words, to delay necking instability. The combined experimental–computational approach provided insight into the relationships between material properties (strength, uniform ductility, and post-necking ductility) and blast resistance of structures. In particular, the approach allowed identification of material/structure performances by identifying impulse-center deflection behavior and the impulse leading to panel fracture.

1. Introduction

Dynamic transverse loading of circular plates has been studied by several investigators and closed form solutions derived to describe plate deflection when subjected to underwater explosions (Cole, 1948; Jones, 1989; Taylor, 1963; Wierzbicky, 1969; Wojno and Wierzbicki, 1980). Recent reviews described available theoretical predictions of the response of loaded plates, accounting for fluid–structure interaction, strain rate effects and energy partition associated to these dynamic events (Nurick and Martin, 1989a,b; Rajendran and Narasimhan, 2006). From these studies, it emerges that performance improvements can be achieved through material optimization (improved strength, hardening rate, uniform ductility, and failure strain). In fact, for a given applied impulse, maximum panel center deflection is inversely proportional to material yield strength. Likewise, uniform ductility controls the onset of necking, which is a precursor to fracture. Hence, high strength materials capable of delaying necking instability are very desirable.

In addition to material improvements, topological structural optimization can also lead to major improvements in performance. For instance, sandwich structures with various core topologies have been investigated to assess the benefits arising from fluid–structure interaction effects (Deshpande and Fleck, 2005; Latourte et al., 2011; Hutchinson and Xue, 2005; Liang et al., 2007; Mori et al., 2007, 2009; Qiu et al., 2004; Vaziri et al., 2007; Xue and Hutchinson, 2003). These studies showed that the performance of sandwich structures is governed by core topology, mass distribution between core and facesheets, and by constitutive material behavior.

To characterize the performance of naval structures, air and underwater blast experiments have been developed. Air blast experiments are relatively simple since they only require an explosive and a foam pad to load the sample (Florence, 1966; Neuberger et al., 2007; Nurick et al., 1996). In water blast experiments, the impulse transfer to the specimen is more complex since fluid–structure interaction effects are prominent. Only a few scaled down experimental approaches have been introduced to study the performance of immersed structures loaded impulsively (Espinosa et al., 2006; Qiu et al., 2004), while full scale experiments are seldom and do not typically provide real time monitoring of

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panel deflection (Rajendran and Narashimhan, 2001). These experimental techniques have revealed that failure of monolithic and sandwich panels include tensile tearing in the central region, transverse shearing failure at the supports, and for certain sandwich panels, facesheet perforation. Hence, optimization of sandwich panel performance is usually achieved by a balance between facesheet integrity on one side, core crushing to enhance the FSI effect, and overall energy absorption capabilities on the other. Likewise, performance of metallic monolithic structures is governed by material strength, uniform and post necking ductility, and hardening and strain rate sensitivity. Therefore, given that materials designed to optimize solid panel performance can also be integrated into the design of sandwich structures, the development of high performance materials can lead to superior combinations of material–structural designs. Such combination was investigated in (Vaziri et al., 2007), where solid panels were numerically compared with sandwich panels, and the influence of the material was examined through different material choices. The study highlighted the trade-off between strength and ductility on panel performance.

Combining strength and ductility is problematic for material designers, but recent advances in material design have been driven by the automotive and naval industries where cost effective, lightweight and resistant structures are desired. In this context, the benefits of the transformation induced plasticity (TRIP) concept have been raised, since the austenite to martensite transformation improves work hardening while maintaining high levels of ductility (Olson, 1996). More generally, new materials where both high strength and ductility are achieved are often designated as advanced high strength steels (AHSS), namely, high strength low alloy precipitation strengthened martensitic steels (HSLA), ferritic–martensitic dual phase steels (DP), and TRIP steels.

This paper deals with the design of different steel alloys and the performance identification of monolithic panels subjected to underwater impulsive loading. We start with a discussion of material design based on deformation modes elicited in structures subjected to blast loading. Then, experimental and computational methodologies, used to investigate material–structural performance when subjected to underwater impulse loading, are described. Results for three steel alloys – the martensitic steel HSLA-100, currently used in naval hulls (Czyryca et al., 1990a; Nichols, 1990), the martensitic steel called blastalloy 160 (BA-160) in (Saha, 2004; Saha et al., 2007; Saha and Olson, 2007), and the fully austenitic TRIP steel called TRIP-120 in (Sadhukhan, 2008) – are presented. Next, a discussion of FSI experimental results and finite element predictions based on an extended Gurson model is provided. The paper closes with a discussion of two approaches to design a novel TRIP steel alloy, which can *simultaneously* achieve high strength, uniform ductility, and failure strains.

2. Material design

2.1. HSLA-100

The high-strength low-alloy steel HSLA-100 was developed by the United States Navy in the early 1990s to reduce fabrication costs in ship construction (Czyryca et al., 1990a,b,c; Nichols, 1990; Sawhill, 1990). In this study, HSLA-100 is used as the reference steel alloy in examining performance improvement. This martensitic steel has similar strength (a yield stress of 100 ksi or 689 MPa) and toughness to the alloy it replaced – HY-100. HSLA-100 was designed with reduced carbon content in order to make it weldable without preheat, which in turn reduces fabrication costs with respect to HY-100. To compensate the reduced carbon content, copper was added to provide an additional precipitation strengthening mechanism (Das et al., 2006; Dunne et al., 1996; Goodman et al., 1973). Copper precipitates also contribute to an increase in the corrosion resistance (Irvine and Pickering, 1963). HSLA-100 processing entails solutionizing, quenching, and tempering at 620–690 °C to obtain a martensitic steel with dispersed Cu precipitates and alloy carbides (Czyryca et al., 1990a,b,c; Nichols, 1990; Sawhill, 1990).

HSLA-100 has been extensively investigated in the past two decades. Studies have been carried out to optimize heat treatments (Dhua et al., 2003) and also to investigate relationships between strength and microstructure (Vaynman et al., 2008). The mechanical performance of HSLA-100 has been characterized through studies of its fracture behavior (Das et al., 2006; Densley and Hirth, 1998) and its ballistic resistance (Martineau et al., 2004).

The HSLA-100 material characterized in this study was provided by Arcelor Mittal, where a 25.4 mm thick plate was hot rolled from a 230 mm thick slab. A typical heat treatment recipe was provided by Arcelor Mittal consisting of a solution treatment at 900 °C for 31 min followed by a water quench, and then aging at 580 °C for 1 h followed by air cooling.

2.2. Blastalloy 160

Blastalloy 160 (BA-160) was designed and developed at Northwestern University and its design and mechanical performance in term of plastic yield stress and impact energy were presented in (Saha, 2004; Saha et al., 2007; Saha and Olson, 2007). Blastalloy 160 was designed using a systems-based design approach to develop a martensitic steel that would meet the projected naval hull material requirements in the year 2020. Design objectives include high strength (160 ksi yield strength), high impact fracture toughness (C_v >115 J corresponding to K_{Id} >220 MPa m$^{1/2}$), good weldability (C content <0.1 wt.%), and high resistance to hydrogen stress corrosion cracking (K_{ISCC}/K_{IC} >0.5). Computational tools were utilized to design a martensitic steel alloy that could achieve all of these property objectives.

In order to achieve the strength goal with limited carbon content to maintain weldability, BA-160 makes use of two precipitate strengthening contributions – fine dispersions of 3 nm M_2C carbides and BCC copper. Quantitative models have been developed for the strengthening contributions that arise from the fine dispersion of M_2C carbide precipitates (Wise, 1998) and BCC copper precipitates (Russell and Brown, 1972). The M_2C carbide strengthening contribution is limited by the carbon content of 0.05 wt.%, which is the carbon level in the current alloy used by the Navy (HSLA-100). With the carbon content set, the sum of the M_2C carbide formers (Cr, Mo, and V) must be twice the carbon concentration for stoichiometric balance. These M_2C carbides were incorporated into the design to dissolve the cementite in the matrix such that strength and toughness goals were achieved. Finally, the required copper concentration was determined to provide the final strengthening contribution to achieve the strength objective. The final design of BA-160 makes use of three strengthening contributions to achieve the strength goal, as shown in Fig. 1c, the martensitic matrix, the M_2C carbide precipitates, and the BCC copper precipitates. Three-dimensional atom probe work has verified the presence of both M_2C carbides and copper precipitates after optimum tempering as shown by the reconstruction in Fig. 1c.

BA-160 also integrates dispersed austenite into its design to increase toughness. Fine dispersions of stable austenite particles delay microvoid nucleation and the onset of shear localization, which is the primary cause of fracture in ultrahigh strength steels (Haidemenopoulos, 1988). In order to maximize the toughening enhancement of dispersed austenite, it is imperative to control the stability of the austenite particles, which is based on the phase fraction, size, and composition of the precipitated austenite. The