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Non linear finite element simulation of explosive welded joints of dissimilar metals for shipbuilding applications

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ABSTRACT

A procedure to simulate the non-linear behavior of explosion welded joints used for shipbuilding applications, starting only from hardness measurements, was developed. The explosion welded joints consist of three different materials: ASTM A516 structural steel, AA5086 aluminum alloy and an intermediate layer of pure aluminum. Three point bending tests were carried out on explosion welded joints with and without an initial notch. The Digital Image Correlation, which is a non-contact full-field technique, was applied in order to measure the displacement and strain patterns of the different metals during the bending tests. Non - linear finite element analyses were performed. The stress-strain curves of the materials, applied in the finite element model, were obtained using Ramberg Osgood type equations and considering the results of the micro-hardness measurements, which were correlated to the mechanical properties of the different materials. The finite element model was validated experimentally, comparing the results with the measurements obtained using the Digital Image Correlation technique. Furthermore, the procedure was extended to a specimen with an initial notch, for which the FE results were compared to the experimental tests.

1. Introduction

Cost, weight, marine corrosion, fatigue and vibrations are only a part of the parameters involved in ships and ocean engineering. Often a single material cannot satisfy all the needed requirements and so, dissimilar materials have to be used. Within this context, the problem of joining different materials arises. Traditional welding techniques often do not give good results in terms of reliability and crack free along the interfaces. The explosion welding (Crossland, 1971) is one of the most performing solutions to join dissimilar metallic materials. One of the most used kinds of explosion welded joints, in shipbuilding industries, is represented by the aluminium/steel type (Ayob, 2010).

The explosion welding process uses an explosive detonation, as energy source, to produce a metallurgical bond between metal components. The two most critical parameters, which influence the weld strength and the interface morphology, are the impact velocity and the impact angle (Botros and Groves, 1980). Generally, due to the difficulty of joining directly aluminium alloy to steel, an intermediate layer is placed in between (Han et al., 2003; Li et al., 2015).

An example of connection using explosion welded joint in ships is reported in Fig. 1.

The literature on the recent developments in explosive welding was reviewed in (Findik, 2011).

A shipbuilding application of bimetallic joints for the connection of aluminium superstructure to steel deck is shown in (Young and Banker, 2004). Experimental investigations of explosive welding of aluminium to steel were reported in literature (McKenney and Banker, 1971; Acarer and Demir, 2008; Raghukandan, 2003).

The interfacial toughness of a shipboard Al/Steel structural transition joint was investigated in (Chao et al., 1997), and it was found that the interfacial toughness increases as the mode II (Shearing mode) increases.

The aim of this research activity was to develop a procedure to simulate the non-linear behavior of aluminium/steel welded joints used in shipbuilding, when they are subjected to bending loading. The need of this procedure arises from the fact that, with these kinds of dissimilar joints, the virgin material properties cannot always be detected from standard tensile tests. For this reason the aim was to build a non-linear FE model, in which the three different materials properties were considered, starting only from hardness tests, which are easy to perform and, more than everything, they are non-destructive. Moreover, another advantage of the developed procedure is that it can be applied also to real ship structures where it is not easy to take samples and make destructive

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Nomenclature

σ_{ut}	ultimate stresses [MPa]
σ_y	yield stress [MPa]
HB	Brinell hardness
HV	Vickers hardness
ε_e	elastic strain
ε_p	plastic strain
E	Young modulus [MPa]
H	material's constant [MPa]
n	hardening exponent of the material
ε_{ut}	ultimate strain
ε_y	yield strain
m, α	material's constants

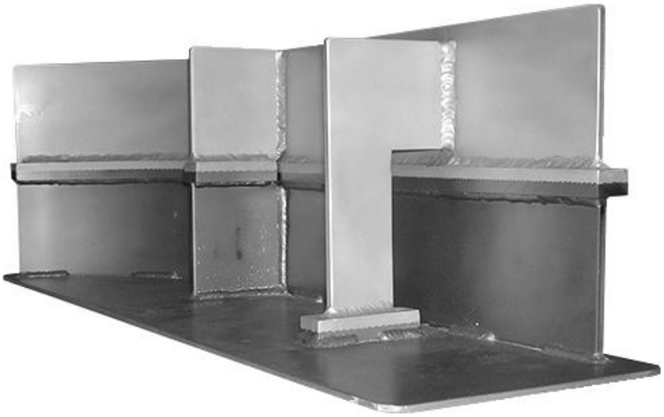

Fig. 1. Example of connection using explosion welded joint in ships.

experimental tests.

The developed procedure is extended, in the present study, to explosion welded joints subjected to three point bending loading, and further applied for the same explosion welded joint with an initial notch in the AA5086 side.

The authors have already applied full-field and non - destructive techniques (Infrared Thermography, Digital Image Correlation, Computed Tomography) for the analysis of different materials and welded joints used for marine structures: welded joints used in shipbuilding under static and low-cycle fatigue loadings (Corigliano et al., 2014, 2015a), aluminum T-shaped welded joints under high cycle fatigue loading (Crupi et al., 2007), high-strength steel and structural steel under static loading (Corigliano et al., 2015b, 2017a), Iroko wood and laminates under static loading (Bucci et al., 2017; Corigliano et al., 2017b).

In the present investigation, the Digital Image Correlation (DIC) technique was applied in order to investigate the influence of the different materials on the mechanical strength of the exploded welded joints during three point bending loading and, above all, in order to validate the non-linear FE model based on hardness measeurements.

2. Hardness measurements and mechanical properties correlation

Hardness measurements were performed in order to investigate the material properties and were directly correlated to mechanical properties.

The investigated explosive welded specimens, produced by TRICLAD, consist of ASTM A516 Gr55 structural steel, clad by explosion welding with AA5086 aluminum alloy and provided with an intermediate layer of AA1050 commercial pure aluminum. The measured hardness values for the three metals are: 175 HV for ASTM A516 gr 55, 47 HV for AA 1050 interlayer, 109 HV for AA 5086. Due to the plasticity induced by the welding process, the microhardness profiles performed around the interface areas showed an increase of hardness, especially at the steel side (Fig. 2).

In the present study, the following relationships of the static mechanical properties (ultimate strength σ_{ut} and yield strength σ_Y) as a function of the Brinell hardness (HB), which were proposed in (Lopez and Fatemi, 2012), were used for the steel:

$$\sigma_{ut} = 0.0012\ \ HB^2 + 3.3\ \ HB \tag{1}$$

$$\sigma_y = 0.0039\ \ HB^2 + 1.62\ \ HB \tag{2}$$

HV values were first converted in HB hardness, then static tensile properties were calculated using eq. (1) and eq. (2) for the steel. Vickers and Brinell hardness values are related by the formula HB = 0.95 HV, valid for steels as reported in (Canale et al., 2008). This relationship is in accordance with the conversion data reported in ASTM E140. The experimental steel hardness data (about 200 HV) are in the range (100–500 HB) considered in (Lopez and Fatemi, 2012). For the AA1050 and the AA5086, typical relationships used for Al alloys, shown in equations (3) and (4), were adopted (Stathers et al., 2014). The results of the profiles, based on microhardness measurements, are reported in Fig. 3.

$$\sigma_{ut} = 2.4079\ \ HV + 46.39 \tag{3}$$

$$\sigma_y = 2.9263\ \ HV - 44.289 \tag{4}$$

The static properties, derived from hardness mesurements, were used in the Ramberg Osgood (R-O) equationsin order to obtain the true stress – strain.

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{H}\right)^{\frac{1}{n}} \tag{5}$$

where ε_e and ε_p are the elastic and the plastic strain, σ [MPa] is the stress; H [MPa] is a material constant equal to σ for $\varepsilon_p = 1$; and n is the hardening exponent of the material.

Considering σ_{ut} [MPa], σ_Y [MPa] ε_{ut}, ε_Y respectively the ultimate and yielding stresses and strains, the parameters H and n can be determined through the following equations:

$$n = \frac{log(\sigma_{ut}/\sigma_Y)}{log(\varepsilon_{ut}/\varepsilon_Y)} \tag{6}$$

$$H = \frac{\sigma_Y}{\varepsilon_Y^n} \tag{7}$$

The yield strain was calculated as σ_Y/E , while ε_{ut} is taken from the datasheet of the materials.

The obtained values are reported in Tables 1–3.

Another method, which uses only the values of the ultimate and yielding stresses (Kamaya, 2016), was applied. The method is based on the Ramberg-Osgood equation type reported in eq. (8):

$$\frac{E\varepsilon}{\sigma_Y} = \frac{\sigma}{\sigma_Y} + \alpha\left(\frac{\sigma}{\sigma_Y}\right)^m \tag{8}$$

Assuming the plastic strain at yielding $\varepsilon_{pY} = 0.002$, α and m are calculated as follows:

$$\alpha = \frac{E\varepsilon_{pY}}{\sigma_Y} \tag{9}$$

In (Kamaya, 2016), the relationship between m and the ultimate and yielding stresses was found equal to: