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Testing and modelling of stiffened aluminium panels subjected to quasi-static and low-velocity impact loading

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ABSTRACT

The behaviour and failure of stiffened panels made of the aluminium alloy AA6082-T6 is investigated under quasi-static and low-velocity impact loading conditions. The strain rate and inertia effects are found to be negligible suggesting that quasi-static tests might be representative for low-velocity impacts where a large mass is placed on the impactor. A simplified approach to the finite element modelling of aluminium panels under impact loading, including a regularised failure criterion, is proposed and validated against the experimental data. The effect of mesh size is investigated with shell elements of various sizes in the range from 1 to 5 times the thickness. A good correlation is obtained between experiments and simulations for fine meshes, while large shell elements have difficulties to initiate and propagate properly the observed cracks.

1. Introduction

Aluminium alloys are important in design of lightweight structures due to their good strength-to-weight ratios. This advantage combined with flexible and cost-efficient extrusion processes have enabled the application of aluminium alloys in several business sectors, including the automotive industry [1] and the oil and gas industry. In the latter, multi-stiffened aluminium panels are used in a wide range of applications from walls and floors in offshore containers to hulls and decks in high speed ferries [2].

As stiffened aluminium panels are often basic building blocks of offshore structures, the research community has addressed the buckling resistance of these components over the past 15 years, e.g. Aalberg et al. [3] and more recently Paulo et al. [4]. At the same time, steel structures have been thoroughly investigated in the literature, with studies including laboratory scaled experiments [5] to full-scale testing [6], analytical developments [7], and modelling and simulation with non-linear finite element techniques [8]. In the latter class of studies, the emphasis has often been on finite element modelling with shell elements of various sizes, as offshore structures are usually rather large and thus prevent the use of fine meshes [9]. A thorough literature review of this particular topic has been recently published by Calle and Alves [10], where the different approaches proposed in the literature for modelling of offshore steel structures subjected to impact scenarios are presented.

Compared to steel structures, modelling of aluminium structures may raise new challenges due to their anisotropic properties [11]. Moreover, structures are usually built from several extruded parts that are welded together. Welding techniques for aluminium structures such as metal inert gas (MIG) welding and friction-stir welding (FSW) introduce heat-affected zones (HAZ) which exhibit lower strength than the base material to be joined [12,13]. These particular features make the simulation of impact loading on aluminium structures using non-linear finite element methods challenging with regards to constitutive modelling.

Over the past decades, the numerical modelling of aluminium alloys has significantly improved with the development of advanced yield functions. An example is the yield function proposed by Barlat et al. [14] which is able to describe the complex anisotropic yielding and plastic flow of most of the aluminium alloys in plane stress states. A drawback of these advanced models is the cost linked to the identification of parameters. Calibration of these yield functions requires at least several tensile tests in different directions with respect to the extrusion or rolling direction, as many parameters are involved in their mathematical formulations. Even if great progress has been made in terms of calibration of these models using for instance crystal-plasticity methods [15–17], the industrial use of such approaches is still challenging and simplified methods are required.

Under impact loading, failure is most likely to occur and has to be accounted for in the design of an aluminium structure. Recent works [18,19] have highlighted that ductile failure in aluminium alloys is strongly dependent on the stress state. Moreover, failure in aluminium alloys can also be strongly anisotropic, as illustrated for the

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AA7075-T651 alloy by Fourmeau et al. [11]. As for the description of complex yielding and plastic flow, several models have been proposed to predict the observed stress state dependent failure of metals [18–20]. While accurate predictions in terms of fracture initiation can be obtained with these models, their calibration requires several material tests under different stress states, thus limiting their applications in an industrial context. Moreover, the full capacity of such fracture models relies on an accurate description of the local plastic flow and strain localization using refined solid element meshes. Therefore, it is not clear that these models would provide significant improvements in the ductile failure prediction when applied in simulations with large shell elements.

This study evaluates the response of stiffened aluminium panels subjected to impact loading. The panels are subjected to quasi-static and low-velocity impact loading using a cylindrical impactor oriented either longitudinally (in parallel) or transversally to the stiffeners. Based on the obtained experimental data, a constitutive model and a failure criterion suitable for numerical simulation of large-scale offshore structures are identified and evaluated using finite element models with different mesh sizes.

2. Material tests

The stiffened aluminium panels are composed of extruded profiles of alloy AA6082 in temper T6. The nominal chemical composition of the alloy is given in Table 1. AA6082 is the most common structural aluminium alloy due its combination of high strength, corrosion resistance and availability as rolled plates and extruded profiles of various form. Moreover, its mechanical properties are comparable in terms of yield strength to regular offshore steels. The aluminium panels are assembled by use of friction-stir welding and each panel consists of five extruded profiles, as shown in Fig. 1. The extruded profile has two stiffeners with a thickness of 3 mm, while the base plate has a thickness of 4 mm. A small increase in thickness is found at both ends of the profile, delimited by a lip (see Fig. 1). The material properties of the base plate and the stiffeners are obtained from tensile testing using the specimen shown in Fig. 2a. The plastic anisotropy of the extruded profile is investigated by performing tensile tests in three directions with respect to the extrusion direction. These tests are done for the base plate only. The macroscopic properties of the heat-affected zone (HAZ) are evaluated using the slightly bigger specimen depicted in Fig. 2b. These tests will be referred as cross-weld tensile tests.

Table 1
Nominal chemical composition of the AA6082 in temper T6.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
Min (%)	0.70			0.40	0.60				0.05
Max (%)	1.30	0.50	0.10	1.00	1.20	0.25	0.20	0.10	0.15

Digital Image Correlation (DIC), using a in-house software [21], and a grip extensometer are applied to measure strains. The gauge length of the extensometer is 35 mm in the tests of the base plate and stiffener material and 57.5 mm in the tests of the heat-affected zone around the welds, respectively. The force is measured by the load cell of the universal testing machines used to perform the tensile tests.

The tensile tests were carried out at a speed of 1.35 mm/min for the base plate and stiffener materials and 2.1 mm/min for the HAZ to ensure a quasi-static strain rate. The engineering stress-strain curves are shown in Fig. 3a for the base plate material and exhibit relatively strong anisotropy of the yield stress. The plastic strain ratios (or Lankford coefficients) are presented in Table 2 and it is evident that also the plastic flow is anisotropic. From Fig. 3b, it can be seen that the stiffener material exhibits a somewhat lower yield stress, while the overall shape of the engineering stress-strain curve is similar to that of the base plate material. It is believed that a difference in cooling rate could be responsible for the lower yield stress as this process parameter can have a large impact on the mechanical properties of a 6xxx alloys.

The engineering stress-strain curve from the HAZ is shown in Fig. 3b. The yield stress is reduced and the work-hardening increased compared with the base plate and stiffener materials. These results are in accordance with existing experimental data for AA6082 in temper T6 [12]. It should be noted that material behaviour within the HAZ is strongly heterogeneous and thus

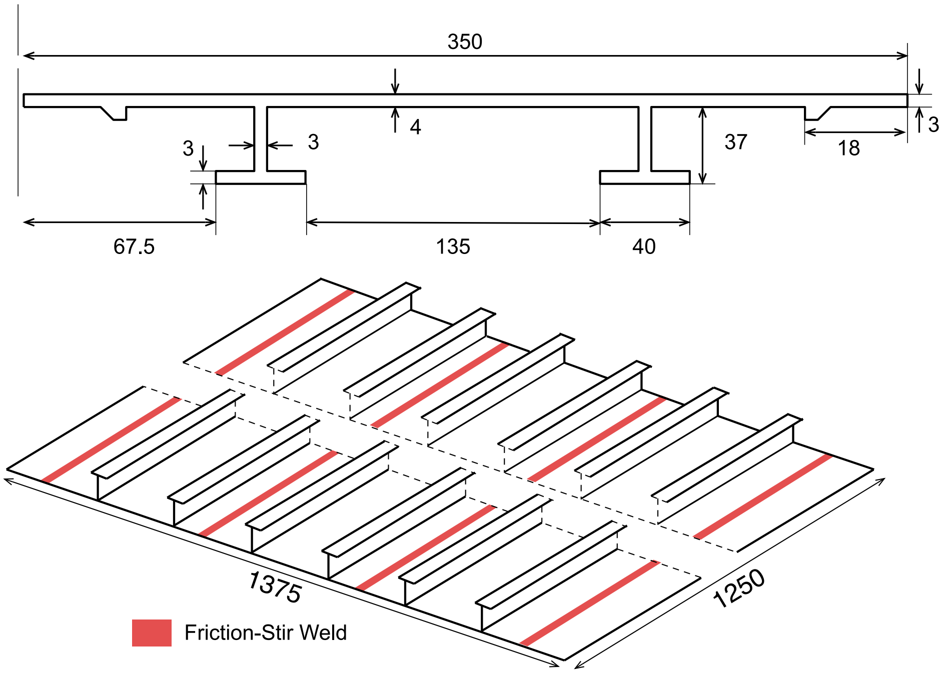

Fig. 1. Illustration of the extruded profile and the assembled panels.

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