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Numerical investigation on the ultimate strength of aluminium integrally stiffened panels subjected to uniaxial compressive load

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ABSTRACT

The objective of this study is to analyse numerically the ultimate strength of stiffened aluminium panels built with extruded aluminium profiles. A finite element code is used to reproduce the mechanical response of the stiffened panels subjected to axial compression. The fabrication related imperfections, such as initial deformations, material softening in Heat-Affected Zone (HAZ) and residual stresses are simulated. The numerical simulations are compared with the experimental response curves, and sensitivity to geometric parameters, initial imperfections and material properties are analysed. The results show that for the considered panel: 1) The ultimate strength is more sensitive to the cross-section dimensions than to the length; 2) The initial deformation has a strong effect not only on the level of ultimate strength but also on the failure mode as well; 3) Both the width of the HAZ and the yield strength in the HAZ has little effect on the ultimate strength of the considered aluminium integrally stiffened panels; 4) The residual stresses will improve the ultimate strength for the considered panels.

1. Introduction

The stiffened panel is widely used in naval architecture and offshore engineering as a basic structural element [1]. The main role of this type of structural component is to resist lateral load and also in-plane compression. Because of the higher ratio of strength-to-weight in comparison with steel structures, aluminium alloy components, including aluminium stiffened panels as well, are increasingly employed in many marine structures instead of steel [2]. According to their manufacturing processes, there are two types of aluminium stiffened panels available [3]. One is the traditional build-up stiffened panels with the stiffeners joined to the skin plate, and the other is the integrally stiffened panels (ISPs) made by aluminium extrusions (extruded profiles) that include the base plate and the stiffener in a single component. Such extrusions eliminate the need to weld the stiffeners to the plate, and the only a longitudinal butt weld is required to join the sections between stiffeners, which is typically done by automatic welding to form large flat decks. Such extrusions are popular for internal decks and weather decks of high-speed vessels and offshore structures.

In structural engineering, understanding the difference between materials in resisting loads requires the knowledge of the materials and their properties. The yield strength of aluminium alloys ranges from 200 N/mm^2 to 600 N/mm^2, and they have about only 1/3 the stiffness of steel. The material properties of the aluminium alloys, including constitutive stress-strain relationship, are different from that of steel. In the case of welded aluminium plates, a heat-affected zone (HAZ) with reduced yield strength and residual stresses in tension is created in the vicinity of the welds, and in the zones further away from the welds a corresponding stress field in compression is present to maintain equilibrium. The material softening in the HAZ significantly affects the ultimate strength behaviour of aluminium structures, while such effect is insignificant [2] for steel structures. Compared to steel panels, the ultimate strength of aluminium panels is sensitive not only to initial deformations and residual stresses, but also to significant changes in the properties of the materials in the HAZ [4].

Mofflin [5] conducted a series of collapse tests on unstiffened aluminium plates. Kristensen and Moan [6] carried out a numerical investigation of the ultimate strength of rectangular aluminium plates under bi-axial loads and discussed the effect of HAZ and residual stresses. Zha and Moan [7] investigated, both experimentally and numerically, the torsional buckling of aluminium flat-bar stiffened panels, and analysed the effects of residual stresses and material softening in HAZ on the buckling behaviour. Numerical simulations and experimental tests were also carried out by Aalberg *et al.* [8] to study the ultimate strength of stiffened aluminium panels under axial

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compression. In addition, stiffened aluminium panels with longitudinal or partial transverse welds have also tested by several researchers [9–13].

Numerical analyses of aluminium panels have been carried out in a number of studies. In the ISSC'2003 III.1 benchmark study, Rigo *et al.* [14] carried out a numerical study of the buckling behaviour of stiffened aluminium panels under axial compression. Based on a series of numerical analyses, Paik and Duran [15] derived an empirical equation for estimating the ultimate strength of welded aluminium panels under compression. Aluminium panels under more complex load forms were also being studied recently [16–20]. Based on numerical studies, Khedmati *et al.* [17] proposed an empirical formula for estimating the ultimate strength of stiffened aluminium panels under combined axial compression and lateral pressure and the influences of geometrical and mechanical imperfections on the ultimate strength was also analysed in [18,19]. Stiffened aluminium panels under combined transverse compression and lateral pressure were also studied by Khedmati et al., [20], who derived, for each case, a set of empirical formulae for predicting the ultimate strength. Paulo *et al.* [21] performed a numerical study of stiffened aluminium panels under axial compression; the sensitivity to initial geometrical imperfections and material properties was analysed. Farajkhah and Liu [22,23] investigated the effect of welding-induced imperfections, including HAZ, residual stress and distortions, on the buckling behaviour of aluminium stiffened panels as well as that on the ultimate strength of aluminium hull girders. There also exist a few studies of stiffened aluminium plates with fixed and floating transverse frames. Khedmati and Ghavami [24] studied the buckling and ultimate strength characteristics, and Li *et al.* [25] determined the ultimate strength using non-linear FE analysis in order to reveal the merits and disadvantages stiffened aluminium plates with transverse floating frames.

From all the literature mentioned above, it can be seen that, the early investigations mainly focused on the ultimate strength or buckling behaviour of traditional build-up aluminium stiffened panels; and in recent years some attention was paid to the ultimate strength and collapse behaviour of ISPs. The main drawback of the traditional kind of stiffened panels is that the effectiveness of the stiffeners is reduced by the HAZ created on the base of the stiffener when welding stiffeners to the plate. With extruded sections the HAZ will be in the middle of the plate between stiffeners, allowing the stiffeners to develop their full capability. However, the contributions about extruded panels are limited [14,16–20] and a systematic sensitivity analysis of the parameters is still to be performed. Therefore, further studies are needed to provide deeper insights into the ultimate strength and collapse behaviour of ISPs under axial compressive load.

The objective of present research is to investigate the ultimate strength of stiffened panels fabricated from aluminium extrusions under axial compressive load. The fabrication related imperfections, such as initial deformations, material softening in HAZ, and residual stresses are simulated. The sensitivities of the obtained results to the geometric dimensions, initial imperfections and yield strength in HAZ are assessed. The effect of initial imperfections focusing on both the amplitude and the shape is investigated in the present work.

2. Numerical model and FE techniques

2.1. Referenced experiment details and model geometry

Aalberg *et al.* [8] conducted a series of compression tests on shipbuilding aluminium ISPs. The experiments were performed by a standard vertical loading frame with displacement control. The test rig, as sketch in Fig. 1, was able to simulate both simply-support and free boundary conditions along the lateral edges of the panels, while the loaded transverse edges are simply supported.

All panels were fabricated from five extruded profiles with L-shaped stiffeners, and were simply supported along the unloaded longitudinal and loaded transverse edges. The cross-sectional geometry of the panels is illustrated in Fig. 2. Before carrying out the tests, the initial deformations (out-of-straightness) were measured at mid-span at the plating side of the panels. The geometries of the three test panels, together with the initial deformations and ultimate strength are summarised in Table 1. Response curves of the measured axial load versus the applied axial displacement are given in Fig. 3, where it is shown that the ultimate strength of the three test panels is below 900 kN. Tensile tests were also carried out using standard coupons taken from the plating and the stiffener walls of the extrusions and also from the weld zones (i.e. HAZ). Fig. 4 depicts the engineering stress versus engineering strain curves of panel materials. No residual stress and width of HAZ measurements were reported.

The test panels introduced above are adopted and re-modelled in this study to further investigate their collapse behaviour. More information about the reference panels, test facility, as well as the results can be found in Aalberg *et al.* [8].

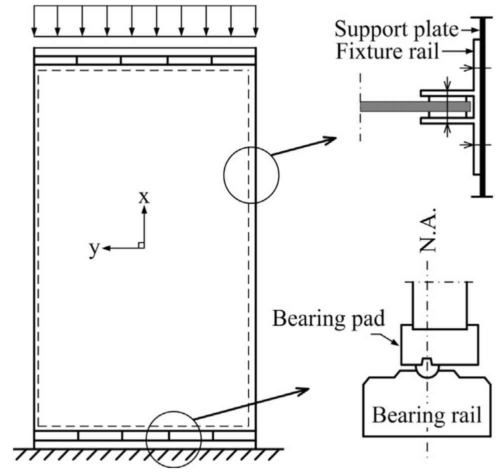

Fig. 1. Test set-up, schematic view of simply supported plate specimen in the test rig, details of support arrangement at unloaded longitudinal edges, and that of cylindrical bearings at loaded ends [8].

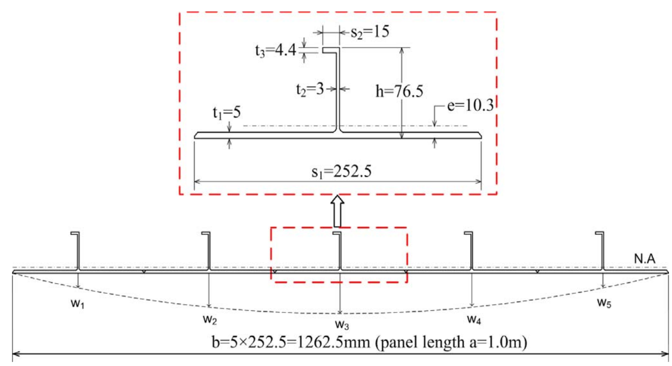

Fig. 2. The cross-section geometry (nominal dimensions) of the panel with L-shaped stiffeners and definition of initial deformations with its reference points [8].

2.2. Boundary conditions and true material properties

The test rig and the specially designed fixtures, as shown in Fig. 1, suggest that the two unloaded longitudinal edges of the ISPs were simply supported and kept straight (constrained edges). The loaded edges were allowed to rotate due to the arrangement of cylindrical bearings at the loaded ends, the axial load (imposed displacement) was applied through the centroid of the panel cross-sectional area (Reference Point A), and axial displacement was fixed at Reference Point B. The implemented boundary conditions in the present study are