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Fatigue strength of thin laser-hybrid welded full-scale deck structure

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ABSTRACT

The fatigue behavior of a 4-mm thick laser-hybrid welded structure was studied using small- and full-scale specimens. The aim of the work was to understand the response and fatigue strength of large thin welded structures. The difference and similarity between small- and full-scale specimens, which is crucial in order to transfer fatigue test results into fatigue design, was carefully studied. The experiments included accurate optical geometry measurements and constant amplitude fatigue testing under axial loading. The fatigue test results were analyzed in terms of structural hot spot stress. The results showed that when initial distortion shape and geometrical nonlinearity are properly considered, the small- and full-scale specimens have equal fatigue strength with small scatter and the same S-N curve slope close to m = 5. In addition, the measured fatigue strength is considerably higher in comparison to IIW structural stress design curve FAT100. This indicates that high fatigue strength can be achieved in thin laser-hybrid welded structures, given that the shape and the magnitude of initial distortion as well as the weld quality are controlled.

1. Introduction

For building more energy-efficient large steel structures such as cruise ships, new lightweight solutions are needed. Plate thicknesses below currently considered limit of 5 mm could be used in selected areas of the structure [1], if modern welding processes with low heat input, e.g. laser-hybrid, are utilized. However, the lack of knowledge about the fatigue resistance, in addition to buckling, vibration and manufacturing considerations, is preventing the rules and recommendations from allowing the use of thin plates in large structures [2,3].

The main challenge with thin-plate structures is caused by their larger and different initial welding induced distortions in comparison to thicker plates [4–6]. Due to lower bending stiffness of the plate itself, the shape of the initial distortion close to the weld is curved. In addition, the curved plate can straighten, i.e. the amount of distortion can reduce during axial tensile loading [4]. This presents special challenges to fatigue assessment. The traditional rule-based fatigue assessment approaches consider ideally straight geometry and include the influence of initial distortion either implicitly in the design curve (nominal stress method) or with a constant beam-theory-based stress magnification factor (structural hot spot stress method). While such approaches work well with thicker plates, they are no longer applicable for thinner ones, where the response is nonlinearly dependent on the distortion shape and magnitude [4,5]. Considering this kind of structural behavior in fatigue assessment is important for all welded thin-plate structures, even if laser-hybrid welding is applied to achieve reduced welding distortions.

Another concern related to thin plates is the weld quality, i.e. higher sensitivity to weld shape [7–9] and flaws such as undercut [10] in comparison to thicker plates. The fatigue strength of laser-hybrid welded joints has recently been investigated in e.g. [5,7,10–14] and most of the studies concentrate on plate thicknesses above 5 mm [11–14]. The results have large variation in case of both thin and thick plates, but with high weld quality it is possible to achieve excellent fatigue strength and small scatter as demonstrated for 4 mm plates in [7]. In addition, the published research shows that the slope is shallower for thin plates in comparison to thicker ones [4,5,7,15].

All these previous studies on thin laser-hybrid welded structures are limited to small-scale specimens of the welded joint. In order to transfer the knowledge from small-scale fatigue tests into the fatigue design, the behavior of a larger thin structure needs to be understood. The effect of varying weld quality in larger structures has not been validated. In addition, unlike small-scale specimens the panels have non-ignorable distortion in two directions of the plate surface. Together with the support from stiffeners and web frames it causes the loads to redistribute [16]. Numerical

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studies on the influence of initial distortion on the response and structural stress in full-scale panels have shown that the butt joint is the most fatigue critical, while the role of the surrounding structure should not be underestimated in providing realistic boundary conditions, [1,16,17]. However, until now no full-scale experiments have been carried out for laser-hybrid welded thin-plate structures.

The goal of this work is to experimentally study the response and fatigue strength of thin large laser-hybrid welded structure. The focus is on the fatigue critical butt joint, while the surrounding plates, stiffeners and web frames are included in order to provide realistic boundary conditions. The loading corresponds to ship hull girder bending, which can be simplified as constant displacement at the edge of the panel as shown in [1]. Full- and small-scale specimens cut from the same panels have been fatigue tested. This paper concentrates on the fatigue strength, while the response is more thoroughly investigated in [18]. The results are analyzed in terms of structural hot-spot stress considering initial distortion shape and geometrical nonlinearity. The difference and similarity between small- and full-scale specimens is carefully studied and discussed.

2. Experiments

2.1. Fatigue test specimens and program

4-mm thick laser-hybrid welded panels shown in Fig. 1 were produced in co-operation with Meyer Turku shipyard and Winnova Oy. The welding sequence was first the butt joint, then stiffeners and finally the web frames. All welds are laser-hybrid, except the connection between the deck plate and the web frame, which was MAG-welded. The heat input of the laser-hybrid welding was 3.5 kJ/cm. The base material is normal structural steel. The mechanical properties and chemical composition of the deck plate are given in Tables 1 and 2, respectively.

The web frame spacing is 2560 mm and dimensions T440 × 7/150 × 10. The bulb profiles HP80 × 5 are spaced 404 mm apart. These structural dimensions represent a typical thin deck structure in cruise ships, guaranteeing adequate buckling strength. In total three thin deck structures were manufactured and 9 full-scale specimens with the overall dimensions of 3360 × 540 mm were cut from them, see Fig. 2. The leftover pieces of the deck plate were utilized to cut 11 small-scale specimens shown in Fig. 3.

The fatigue critical butt joint located in the middle of the web frame spacing is presented in Fig. 4. The weld geometry is smooth even in cases where noticeable axial misalignment is present. The mean geometry of the butt joint is defined from small-scale specimens and the dimensions are given in Table 3. Also the Vickers hardness HV1 defined in accordance with [19,20] is well below the limit value of 380 in DNV rules [21] throughout the measurement path. The weld quality is reflecting the modern laser-hybrid welding in shipyard production environment.

Table 1
Material properties of the base plate.

	Yield strength R_{eH} (MPa)	Ultimate tensile strength R_m (MPa)	Failure strain A (%)
Plate t = 4 mm	320	458	34

2.2. Geometry and residual stress measurements

Geometry measurements for both small- and full-scale specimens were carried out using Gom Atos optical system with two cameras. The minimum accuracy of the measurements was 0.02 mm. The small-scale specimens were measured from both sides to capture the plate distortion and the weld shape. The full-scale specimens were measured in full length only from stiffener side to capture the overall plate distortion. The fatigue critical butt joint area in the middle of the web frame spacing was measured from both sides. The accurately measured geometry was utilized to create finite element (FE) models.

In order to understand the possible differences in fatigue strength, also the residual stress and its relaxation under loading was measured in both full- and small-scale specimen using X-ray diffraction in accordance with [22]. The measurement points were in the middle of the specimen close to fatigue critical notch of the butt joint. The first measurement point was as close to the weld notch as possible with collimator edge almost touching the notch. The next measurement points were on a perpendicular line to the weld, spaced 1 mm apart for panel and 3 mm apart for small-scale specimen. The collimator size was 2 mm in panel and 3 mm in small-scale specimen. For comparison also 1 mm collimator size was tested, but differences were insignificant.

2.3. Fatigue tests

The small-scale specimens were tested using hydraulic MTS 810 testing machine. The load frequency was 10 Hz and the load ratio R = 0. The same test setup was utilized as previously reported for small-scale specimens in e.g. [4,5]. Special rotating clamps were used to avoid additional bending stress due to angular misalignment during clamping. After clamping the rotation was fixed. The strains were measured with two 5-mm strain gauges approximately 6 mm from the weld notch at both sides of the plate to also capture the bending part. In addition to strain the force and number of cycles were recorded. Number of cycles to failure was defined at final fracture. The run-out limit was set to 2 million load

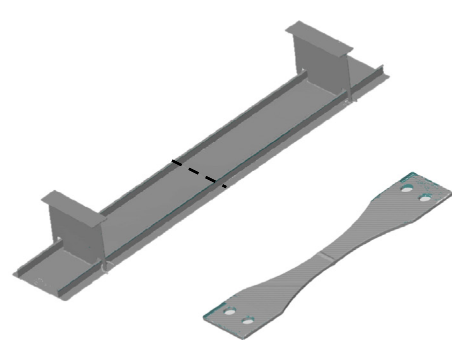

Fig. 1. 4-mm thick laser-hybrid welded stiffened panel and full- and small-scale specimen.