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Fatigue strength of laser-welded thin-plate ship structures based on nominal and structural hot-spot stress approach

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To improve the energy efficiency, the demand for new light-weight solutions has been increased significantly in the last decades. The weight reduction of the current ship structures is possible using thinner plates, that is, plate thickness between 3 and 4 mm. However, at present this is, in normal cases, not possible due to the 5 mm minimum plate thickness requirement given by classification societies. The present paper investigates the fatigue strength of thin-plated ship structures. In the European research project BESST – 'Breakthrough in European Ship and Shipbuilding Technologies' – the extensive fatigue test programme was carried out for butt- and fillet-welded specimens, which were manufactured by the arc, laser and laser-hybrid welding methods. The test programme also covered the different production quality and thus a large variation of misalignments was included. Fatigue test results were analysed using the nominal as well as the structural stress approach, where the actual geometry of the specimens was taken into account. The results show that the present design *S–N* curve with slope value of 3 is applicable to thin plates, but it is slightly non-conservative. The fatigue test results for thin plates show better agreement with the slope value of 5. For thin plates and slender ship structures, the secondary bending stress due to angular misalignment plays an important part and changes in a non-linear way with the applied tension load. Therefore, it is important to consider the plate straightening effect in structural stress analysis.

Keywords: fatigue strength; thin plate; laser-welded joint; structural stress approach

1. Introduction

In order to increase the energy efficiency, the demand for new light-weight solutions has been increased significantly in the last decades. The weight reduction of the current ship structures is possible using thinner plates, that is, down to plate thicknesses of 4 mm or even 3 mm. However, at present the use of thin plates is in normal cases not allowed due to the 5 mm minimum plate thickness requirement given by classification societies.

In thin plates, one of the main challenges is distortions caused by fabrication process. Especially, axial and angular misalignments are commonly significantly larger for thin than thick plates (Eggert et al. 2012; Lillemäe et al. 2012). However, if low heat-input welding such as laser welding is used instead of conventional arc welding, the amount of misalignments can be reduced (Roland et al. 2004). The misalignments are harmful since they cause secondary bending stress on the weld notch reducing the fatigue strength of the joint.

The fatigue strength of thin welded plates has been studied in several papers (Eibl et al. 2003; Radaj et al. 2009; Sonsino et al. 2010). These studies focused mainly on the automotive industry application, the production of which differs from ship production. In the production of large ship structures, the control of the distortion is significantly more difficult. Therefore, further investigation is needed to develop a solid design basis for the fatigue strength assessment of thin ship structures.

This paper investigates the fatigue strength of thin ship structures welded by the arc, laser and laser-hybrid welding methods. The special emphasis of the study is paid on the influence of the misalignments on the fatigue strength. Therefore, the different production quality is simulated having a large variation of misalignments. The extensive fatigue test programme was carried out for butt- and fillet-welded specimens within the European research project BESST (Breakthrough in European Ship and Shipbuilding Technologies). Fatigue test results were analysed using the nominal as well as the structural hot-spot stress approach, where the actual geometry of the specimens was taken into account. This investigation focuses on the fatigue strength of the welded joint and, thus, the effects of surrounding structures are neglected.

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2. Fatigue experiments

2.1. *Fatigue test programme*

The summary of the fatigue test programme is presented in Table 1. The investigations were focused on the plate thickness t between 3 and 5 mm. Different laser welding arrangements and edge preparations suitable for the shipyard production were covered. The test programme also included some conventional arc-welded, that is, submerged arc, flux-cored arc and metal active gas (SAW, FCAW and MAG, respectively) welded joints and 6–8 mm thick joints for comparison. The heat input is given in Table 1. In total, 14 different butt joint and 14 different T-joint series were tested. For each test series, about 10 specimens were fabricated out of welded plates produced at 4 shipyards. The base plates had the yield strength R_{eH} between 293 and 466 MPa. The tensile strength R_m of the base plates was between 439 and 572 MPa, and the failure strain A was 31% on average. The produced test specimens were tested under transversal or longitudinal loading. The load ratio of $R = 0$ was applied. In some tests, where test arrangements (four-point bending) did not allow $R = 0$, other R values were chosen. The test programme also included some series which were tested with the load ratio of $R = 0.25$ and 0.5 for comparison.

2.2. *Geometry measurements*

Geometry measurements were carried out with the optical measuring technique using high-resolution cameras or laser scanners. Details of the devices are described by Lillemäe et al. (2012) and ATOS (2011). The geometry points on the top of the specimen surfaces were recorded and numerical three-dimensional (3D) models of the specimen were created. From the 3D model the section perpendicular to the weld seam was generated for two-dimensional (2D) structural stress analysis (Lillemäe et al. 2012). From the geometry measurement data, the axial and angular misalignments of the joints are defined as shown in Figure 1.

2.3. *Fatigue tests*

Constant amplitude fatigue tests were carried out using hydraulic and resonance test machines. Special clamping jaws were applied to avoid additional bending stresses during clamping (see Figure 2). The load frequency was 10 Hz for the hydraulic test machines and 30 Hz for the resonance test machines. During the tests, applied force and number of load cycles to failure were recorded. The number of cycles to failure was defined at the occurrence of the final fracture. The nominal stress was defined as the force divided by the cross-sectional area of the plate in the middle of the specimen.

3. Structural stress analyses

The structural hot-spot stresses for the measured joint geometries were calculated using the finite element method. The analysis was performed according to guidelines of the International Institute of Welding (Hobbacher 2009). A 2D plane stress element model was created for each of the test specimens. ANSYS 13.0 and Abaqus 6.11 – two softwares with geometrical non-linearity – were used, where the load is applied step by step and the geometry is intermediately updated according to the straightening of the specimen. A linear elastic material behaviour with Young's modulus of 206,800 MPa and Poisson's coefficient 0.3 was assumed. The finite element simulations were validated by the measured strains at the specimen surface (Lillemäe et al. 2012).

4. Results

4.1. *Joint geometry*

The measured axial and angular misalignments are summarised in Figures 3–5. The minimum, average and maximum values are presented for each test series. The results are compared with the limit values of the quality classes B, C and D according to ISO 5817 (2003). The limit values of angular misalignment refer to the standard version until 2006.

The axial misalignment of the butt-welded joints, shown in Figure 3, varies between different joints. For all conventionally arc-welded joints, the maximum values are above the $e/t = 0.15$ limit. For the hybrid- and laser-welded joints almost all of the axial misalignments are within the $e/t = 0.1$ limit. In this comparison, the thickness step-induced axial misalignment was neglected.

The angular misalignments given in Figures 4 and 5 reveal similar behaviour. For conventionally welded joints, the angular misalignments were significantly larger than those of hybrid- and laser-welded joints. For the conventional welded joints, the maximum absolute value is 6.7°. For hybrid- and laser-welded joints the absolute maximum values are 2.2° and 1.8°, respectively. In general, the average value of the angular misalignments is higher for T-joints than for butt-welded joints.

4.2. *Fatigue strength*

The fatigue test results can only be shown in a summary here. As expected for relatively thin-plated joints, the axial and angular misalignments affect the fatigue lives considerably. Therefore, the test specimens were associated to three classes according to ISO 5817 mentioned above:

- Misalignment low: if $e/t \leq 0.1$ and $\alpha \leq 1°$.
- Misalignment medium: if $0.1 < e/t \leq 0.15$ and/or $1° < \alpha \leq 2°$.
- Misalignment high: if $e/t > 0.15$ or $\alpha > 2°$.

Table 1. Fatigue test programme.

Series	Joint description	Heat input	No. of	Loading	Properties of base plate/stiffener			
Symbol	Welding method	(kJ/cm)	specimens	Type	t (mm)*	R_{eH} (MPa)	R_m (MPa)	A (%)
B.3.LA.1	Laser-welded butt joint	2.4	10	Transv., $R = 0$	3	414	567	24.7
B.3.HY.1	Laser-hybrid-welded butt joint	1.6	10	Transv., $R = 0$	3	399	531	26
B.3.CV.1	Conventionally arc-welded butt joint, block joint	9.0**	10	Transv., $R = 0$	3	466	564	31
B.3.CV.2	Conventionally arc-welded butt joint	7.0**	9	Transv., $R = 0$	3	466	564	31
B.3.CV.3	Same as B.3.CV.2, but faired after welding	13.0**	11	Transv., $R = 0.5$	3	408	490	41
B.35.LA	Laser-welded butt joint, thickness step	3.0	10	Transv., $R = 0$	3/5	466/432	564/521	31/30
B.35.HY	Laser-hybrid-welded butt joint, thickness step	4.0	9	Transv., $R = 0$	3/5	466/432	564/521	31/30
B.35.CV	Conventionally arc-welded butt joint, thickness step	3.5	11	Transv., $R = 0$	3/5	466/432	564/521	31/30
B.4.LA.1	Laser-welded butt joint	3.3	10	Transv., $R = 0$	4	443	547	31
B.4.LA.2	Laser-welded butt joint	3.3	10	Transv., $R = 0.5$	4	443	547	31
B.4.HY.1	Laser-hybrid-welded butt joint	1.7	15	Transv., $R = 0$	4	414	537	24
B.4.CV.1	Conventionally arc-welded butt joint	15.5**	13	Transv., $R = 0$	4	356	474	34
B.4.CV.2	Same as B.4.CV.1, but faired after welding	15.5**	10	Transv., $R = 0$	4	356	474	34
B.6.HY.1	Laser-hybrid-welded butt joint, plasma cut edges	5.3	11	Transv., $R = 0$	6	343	472	34
F.35.LA.1	Laser-welded T-joint	4.3	8	Transv., $R = 0$	3/5	399/400	531/533	26/33
F.35.HY.1	Laser-hybrid-welded T-joint	4.7	9	Transv., $R = 0$	3/5	348/358	439/492	39/29
F.35.HY.2	Laser-hybrid-welded T-joint, one-side weld	4.7	10	Transv., $R = 0.25$	3/5	348/358	439/492	39/29
F.35.CV.1	Conventionally arc-welded T-joint	7.5**	8	Transv., $R = 0$	3/5	466/432	564/521	31/30
F.35.CV.2	Conventionally arc-welded T-joint, one-side weld	4.3	7	Transv., $R = 0.25$	3/5	348/358	439/492	39/29
F.35.CV.3	Conventionally arc-welded T-joint	4.3**	8	Long., $R = 0.1$	3/5	399/400	531/533	26/33
F.85.LA.1	Laser-welded T-joint	4.3	11	Transv., $R = 0$	8/5	384/400	546/533	28/33
F.85.HY.1	Laser-hybrid-welded T-joint	4.7	13	Transv., $R = 0$	8/5	293/377	445/514	30/23
F.85.HY.2	Laser-hybrid-welded T-joint	4.7	7	Transv., $R = 0.25$	8/5	293/377	445/514	30/23
F.85.HY.3	Laser-hybrid-welded T-joint	4.7	7	Transv., $R = 0.5$	8/5	293/377	445/514	30/23
F.85.CV.1	Conventionally arc-welded T-joint	9.3**	9	Transv., $R = 0$	8/5	333	450	40
F.85.CV.2	Conventionally arc-welded T-joint	4.3**	7	Long., $R = 0.15$	8/5	384/400	546/533	28/33
F.87.LA.2	Laser-welded T-joint	6.9	10	Transv., $R = 0$	8/7	384/448	546/572	28/29
F.87.HY.1	Laser-hybrid-welded T-joint	5.7	11	Transv., $R = 0$	8/7	293/336	445/470	30/32

*Two values characterise either a thickness step or give the thicknesses of the base plate and stiffener of T-joints.
**For both welds.

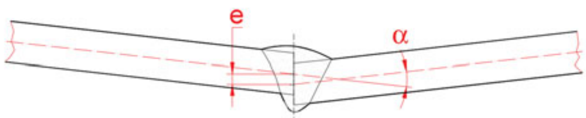

Figure 1. Axial e and angular α misalignments. (This figure is available in colour online.)

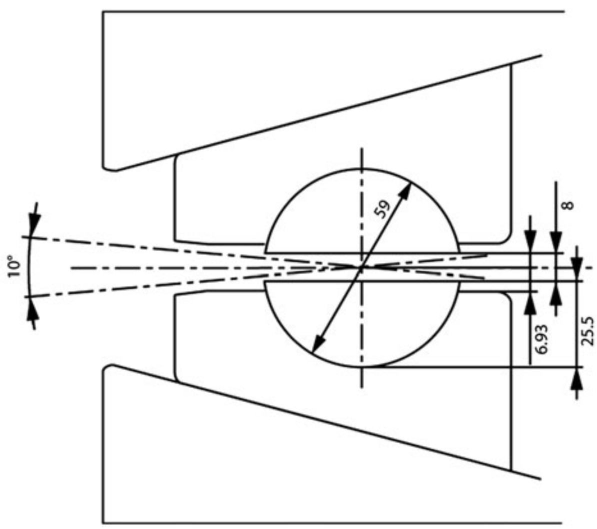

Figure 2. Example of clamping jaw with rotating ability during clamping.

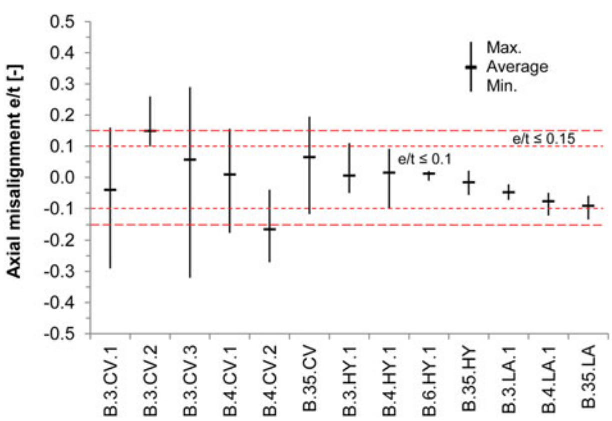

Figure 3. Axial misalignments of butt-welded joints. (This figure is available in colour online.)

The results based on the nominal stress acting in the test specimens are shown for the butt joints in Figures 6–8 separately for those welded conventionally (CV), with laser-only (LA) and with laser-hybrid processes (HY). It can be seen at a first glance that the majority of CV belongs to the class with the highest misalignment, whereas the majority of LA belongs to the lowest and HY to the intermediate. An influence of the misalignment class is particularly large for CV, but also visible for LA.

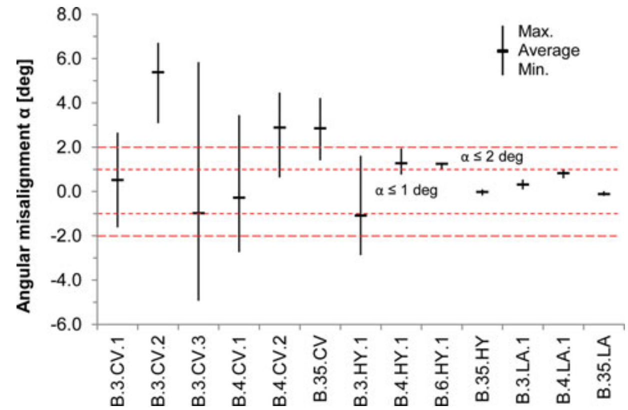

Figure 4. Angular misalignments of butt-welded joints. (This figure is available in colour online.)

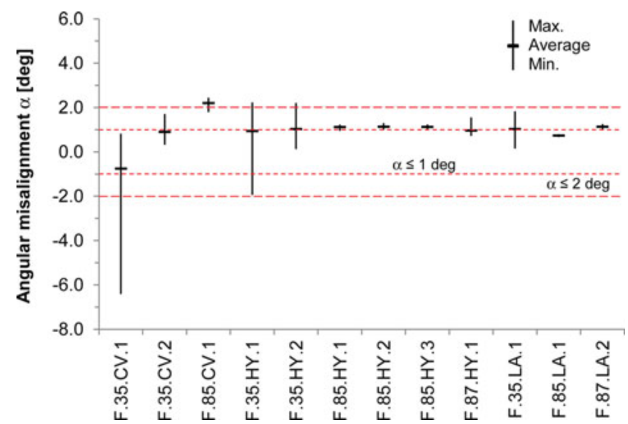

Figure 5. Angular misalignments of fillet-welded T-joints. (This figure is available in colour online.)

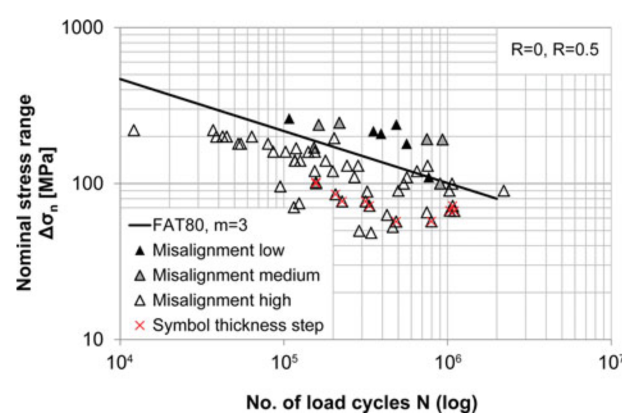

Figure 6. Fatigue test results for conventionally welded butt joints based on nominal stress. (This figure is available in colour online.)

In the *S–N* diagrams the specimens with thickness step which induce an additional misalignment and which usually belongs to a lower fatigue class according to the nominal stress approach are indicated. Also, the design *S–N* curve

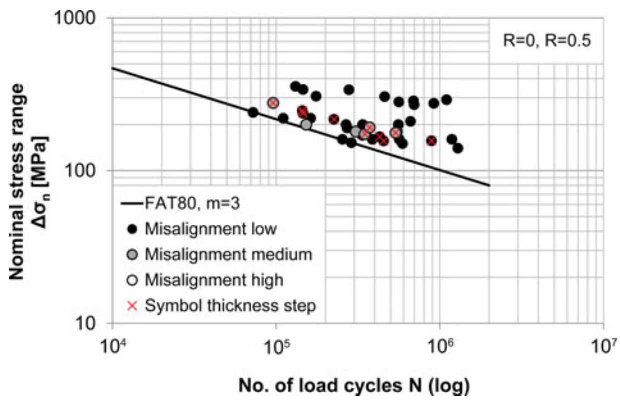

Figure 7. Fatigue test results for laser-only-welded butt joints based on nominal stress. (This figure is available in colour online.)

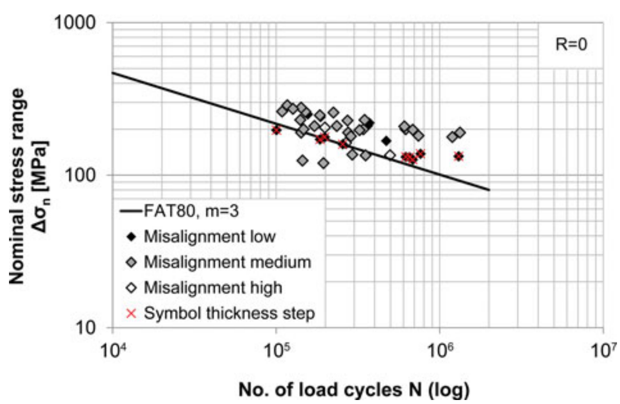

Figure 8. Fatigue test results for laser-hybrid-welded butt joints based on nominal stress. (This figure is available in colour online.)

FAT80 (80 MPa at 2×10^6 cycles) which is usually applied to butt joints not meeting higher requirements regarding, for example, weld reinforcements is included. All specimens with small misalignments and without thickness step are above FAT80, whereas those with higher misalignments are partly far below the FAT80 line.

The fatigue test results for the T-joints based on nominal stress are plotted in Figures 9–11, again separately for the three welding processes. Here, only angular misalignment is possible. An effect of the welding process can be seen in all cases. Almost all specimens with low angular misalignment meet the design *S–N* curve FAT80 commonly used for transverse stiffeners, whereas those with higher misalignments are below this curve, particularly for CV and HY. Another observation is that the slope of the *S–N* results is obviously flatter than that of the design *S–N* curve ($m = 3$), which was previously observed particularly for thin-walled components resulting in a proposal of $m = 5$ (Sonsino et al. 2010).

In addition to the nominal stress approach, the structural hot-spot stress approach was also applied, which considers the effect of secondary bending stress due to misalignment in the structural stress. The results based on the structural hot-spot stress approach are plotted in Figure 12 for all butt joints and in Figure 13 for all T-joints.

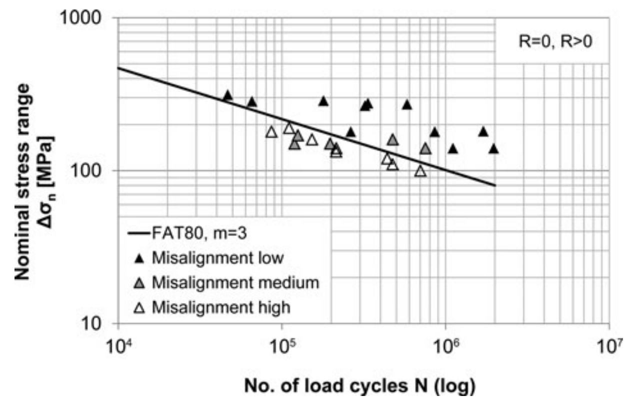

Figure 9. Fatigue test results for conventionally welded T-joints based on nominal stress.

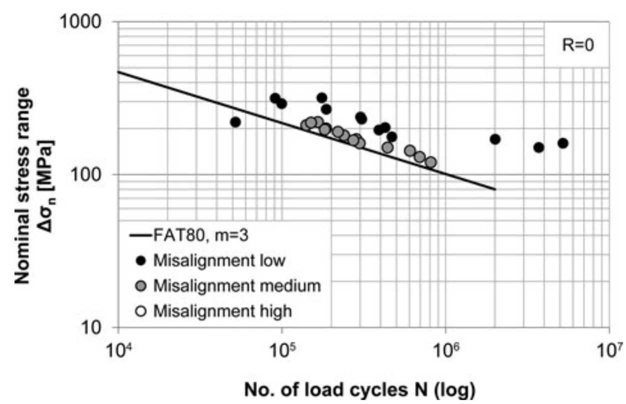

Figure 10. Fatigue test results for laser-only-welded T-joints based on nominal stress.

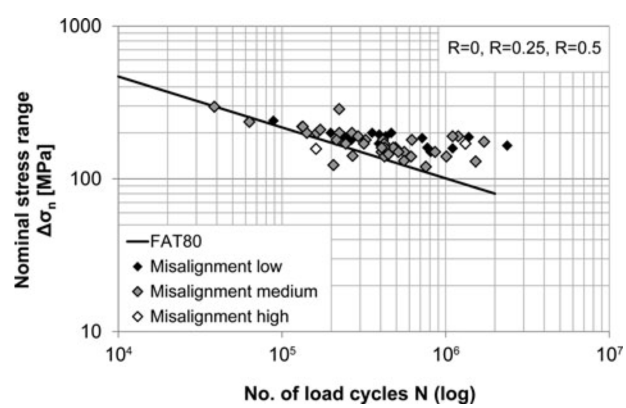

Figure 11. Fatigue test results for laser-hybrid-welded T-joints based on nominal stress.

Almost all test results are above the design *S–N* curve FAT100 proposed by Hobbacher (2009) for the structural hot-spot stress approach. Pronounced differences between the different welding processes and misalignment classes are not visible except for T-joints, where laser welding seems to show slightly better results.

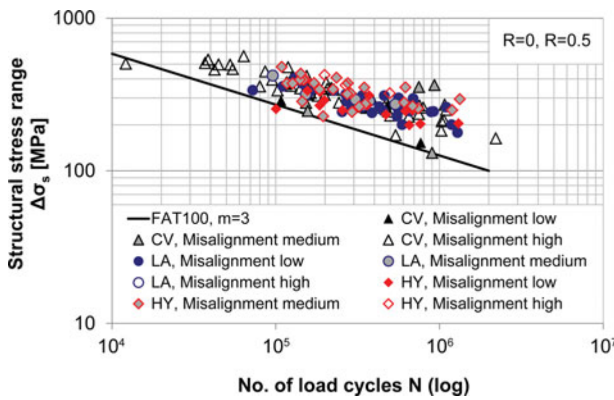

Figure 12. Fatigue test results for all butt joints based on structural hot-spot stress. (This figure is available in colour online.)

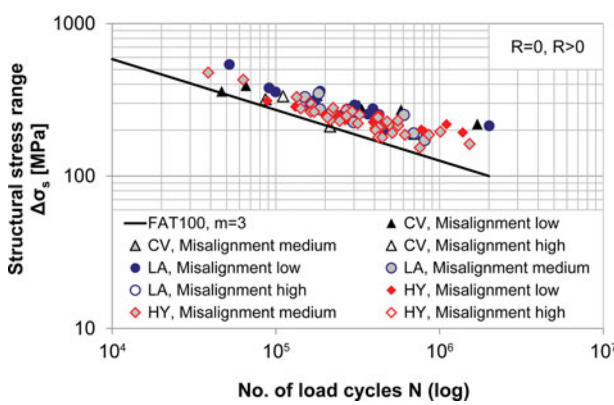

Figure 13. Fatigue test results for all T-joints based on structural hot-spot stress. (This figure is available in colour online.)

5. Discussion and conclusions

Extensive fatigue tests were performed for butt joints and T-joints welded conventionally, with LA and HY. The welding was performed by different European shipyards using thicknesses between 3 and 8 mm for the base plates. Axial and angular misalignments could not be avoided with these plate thicknesses and these were recorded for each specimen.

From the fatigue test results, which were evaluated according to the nominal and the structural hot-spot stress approaches, the following conclusions can be drawn:

- The misalignments considerably affect the fatigue strength if based on the nominal stress approach.
- The fatigue strength based on nominal stress is above the fatigue class FAT80 used in codes as long as the misalignments are relatively small, which is the case for almost all laser-welded joints.
- Relatively large misalignments have been observed particularly for conventionally welded joints resulting in fatigue strength below the fatigue class FAT80.
- Based on the structural hot-spot stress, which includes the effects of misalignments, almost all results are above the relevant fatigue class FAT100. Here, the differences between the different welding processes are small.

A more refined evaluation of the fatigue test results and further influence factors on fatigue strength is beyond the scope of this paper. Such investigations have been performed being published in separate papers, such as Lillemäe et al. (2012). Conclusions regarding the implementation of the results into classification rules are drawn by von Selle et al. (2013).

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