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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 IWF 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].

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
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 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 7/150 x 10. The bulb profiles HP80 x 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 size specimens with the overall dimensions of 3360 x 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.

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.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Material properties of the base plate.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield strength Rm (MPa)</td>
</tr>
<tr>
<td>Plate t = 4 mm</td>
<td>320</td>
</tr>
</tbody>
</table>

Fig. 1. 4-mm thick laser-hybrid welded stiffened panel and full- and small-scale specimen.
cycles. Before fatigue testing 10 slower cycles were performed with the frequency of 1/40 Hz to check the strain signal and validate the FE analysis.

For full-scale specimens a horizontal test setup shown in Fig. 5 was built utilizing large I-beams and 1 MN hydraulic force cylinder. The specimen was fixed between the cylinder in one end and force sensor at the other with pivoted connections. The purpose of the thick clamping plates was to apply the force to neutral axis of the panel. The L-profiles bolted to the clamping plates and stiffeners distributed the load proportionally between the deck plate and stiffeners, corresponding to realistic loading in case of ship hull girder bending, see also [1].

For all panels 12 5-mm strain gauges were applied at approximately 6–10 mm from the weld notch. 10 strain gauges were located on the top side of the deck plate, i.e. more fatigue critical weld root side according to geometry measurements, and 2 on the stiffener side, see Fig. 6. In addition to strains also cylinder displacement, force and number of cycles were recorded. The number of cycles to failure for full-scale specimens was also defined at the final fracture into two pieces. Before fatigue testing at least 4 slower cycles with the frequency of 1/60 Hz were carried out for verifying proper strain measurement and validating the FE analysis. The load frequency in the fatigue test was 0.5 Hz and the load ratio R = 0.1.

### 2.4. Structural analysis

#### 2.4.1. Response analysis

The stresses and strains in thin panels were calculated using geometrically nonlinear FE analysis considering the initial distortion shape. The results were compared with the recorded values from the strain gauges and with the visible crack growth locations. For creating the FE models first the geometry points at every 10 mm were extracted from the original data of Gom Inspect software. The initially straight FE model was modified to correspond to the measured initial distortions by applying nodal displacements on the plating and solving the model. The resulting deformed geometry was then used as an initial geometry for the final model, i.e. there were no stresses before applying the axial loading from the test setup, see also the flow chart of the modeling process in Fig. 7. The model was created with four-node shell elements (S4R in Abaqus) and the mesh size was about 5 mm close to butt weld and 10 mm elsewhere, which proved to be fine enough to represent the initial distortion shape. In fatigue critical areas close to butt weld the geometry from FE model was compared with the original data and manually corrected where necessary in order to guarantee the accurate shape.

For applying axial loading two modeling approaches were compared. In the first the clamping plates were also modeled, see Fig. 8.

---

**Table 2**

<table>
<thead>
<tr>
<th>C (%)</th>
<th>Si (%)</th>
<th>Mn (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Al (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.149</td>
<td>0.20</td>
<td>0.90</td>
<td>0.010</td>
<td>0.008</td>
<td>0.038</td>
</tr>
</tbody>
</table>

---

![Fig. 2. Full-scale specimen.](image)

![Fig. 3. Small-scale specimen [7].](image)
Fig. 4. Macro-graph and hardness distribution in laser-hybrid welded butt joint with large (a) and minor axial misalignment (b).

Table 3
Mean weld geometry of the butt joint.

<table>
<thead>
<tr>
<th>Weld</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Flank angle (°)</th>
<th>Radius (mm)</th>
<th>Undercut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOE</td>
<td>5.4</td>
<td>1.2</td>
<td>17</td>
<td>1.04</td>
<td>0.04</td>
</tr>
<tr>
<td>ROOT</td>
<td>4.3</td>
<td>0.9</td>
<td>27</td>
<td>0.73</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig. 5. Setup for full-scale tests.
and in the second simplified boundary conditions were applied at approximately 100 mm outside web frames, where the clamps ended. Displacements and rotations of both ends were fixed except the axial displacement of the loaded end where axial force was applied. As these two modeling approaches revealed negligible difference, the simplified one was applied for most of the panel specimens. Analyses were carried out using Abaqus 6.13 FE software and pre- and post-processing using Femap 11.0. Linear elastic material behavior with Young's modulus of $E = 206.8$ GPa and Poisson's ratio of $\nu = 0.3$ was assumed.

### 2.4.2. Structural hot spot stress analysis

For structural hot spot stress analysis of full-scale specimens, local 2D plane stress models were created both for maximum normal strain as well as crack initiation location along the butt weld, see Fig. 13 and Table A.2 in Appendix A. In cases where exact crack initiation location was not clear due to several early crack growth sites, the possible initiation area was determined and many local models in that area were created. Then the maximum structural hot spot stress from all of the models was chosen. The length of the local models was approximately 140 mm. The mesh size was about 0.1 mm close to weld and gradually increased to 0.8 mm at the ends of the model. The loading for the local 2D plane stress models was defined as nodal displacements from the global panel model. The whole FE-analysis procedure for full-scale specimens is presented in Fig. 8.

Small-scale specimens were analyzed geometrically nonlinearly to account for the straightening effect under loading as instructed in [4]. The average geometry for each specimen was defined from at least 20 2D sections cut from 3D model as shown in [7]. The model was created using plane stress elements with linear shape functions and the mesh size in the weld region was 0.2 mm.

For both small- and full-scale specimens the analysis was carried out with Abaqus 6.13 FE software and linear elastic material behavior with $E = 206.8$ GPa and $\nu = 0.3$ was assumed. The nominal stress was defined as applied force divided by cross-sectional area. The hot spot stress was defined using linear extrapolation of maximum principal stress to the weld notch. The extrapolation points were at distances 1.6 mm (0.4t) and 4 mm (1.0t) from the fatigue critical notch as suggested by IIW [3]. Out of 4 notches the crack initiation and maximum stress location according to FE analysis always matched.
3. Results

3.1. Geometry of thin panels

Fig. 9 presents the distortion shape at the middle of the small-scale specimens. All specimens have the angular distortion in the same direction. Based on this, the weld root side, i.e., the bottom side in the figure, is more fatigue critical. In addition, some specimens have large axial misalignment, which dictates the side of the failure, i.e., left or right. The average axial misalignment in relation to plate thickness is $e/t = -0.04$, which is less than the most stringent limit of $e/t < 0.1$ given in ISO standard for laser-hybrid welds [23]. The determination of angular misalignment is difficult for thin plates due to their curved shape. The exact values are dependent on the distance between the weld and the observation points.

The distorted shapes of all panels in longitudinal direction in the middle of the stiffener spacing are given in Fig. 10 and in transverse direction at $y = 100$ mm in Fig. 11. The initial distortion of about 2 mm around the butt weld is quite moderate in comparison to previously reported values of up to 8 mm for arc-welded panels in [6]. The roof-like shape close to butt-weld makes the deck plate side (bottom side in the figure) more fatigue critical. The larger distortion at the ends of the panel outside web frames is not making

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**Fig. 8.** Finite element analysis procedure from panel response (a) to structural hot spot stress extrapolation (b), example on panel 234.

**Fig. 9.** Initial shape of small-scale specimens, sections taken from the middle of the specimen.
the fillet weld between the deck plate and the web fatigue critical as beneficial compressive stress is induced under tensile axial load. The problem of determining angular misalignment is even more visible in full-scale specimens as the whole shape is important, not only the angle at a certain location. A complete geometry of one panel (334) is appended to this article as supplementary material.

Fig. 12 presents the transverse residual stresses and their relaxation under loading. Initially compressive residual stresses of about 1/3 of the yield stress are present close to fatigue critical notch in both full- and small-scale specimen. After the first cycle the residual stress relaxed to about half in both full- and small-scale specimen and then stabilized. The residual stress relaxation is in very good agreement with the experimentally-based relaxation model presented in [24]. Considering the uncertainties related to residual stress measurements by X-ray diffraction and the fact that it is not possible to capture stresses in the weld notch, but only at some distance away from it, the purpose of the study was just to qualitatively estimate the possible differences between full- and small-scale specimens. These results indicate that the residual stress state of thin full- and small-scale specimen is similar.

3.2. Response of thin panels

In Fig. 13 the normal strain from the FE-analysis is compared with the strain gauge values from the experiments at the fatigue critical side of the weld. It can be seen that if the initially distorted geometry is carefully modeled, the strain distribution agrees very well with the experiments. The maximum difference was observed to be 8%, while the average was 2.4%. The estimated crack initiation locations were also in line with the experiments. All 9 panels failed
from the weld root of the butt joint as expected based on the geometry measurements and FE-analysis. Typically, several crack initiation locations were observed in fracture surfaces. Examples of the fracture surfaces are given in Fig. 14 for panel specimen 256 and Fig. 15 for 356. In the first example a typical wide early crack growth area is visible and the exact initiation location is difficult to be determined. In the second case, an exceptional smaller dominant crack initiation area is observed.

3.3. Fatigue strength

The fatigue strength in terms of nominal stress together with the IIW design curve FAT80 [3] is plotted in Fig. 16. The results have large scatter because of the unaccounted variation in initial distortion and therefore, the statistical curves cannot be fitted reliably to such limited number of data points. In addition, some tests fall below the IIW design curve. Therefore, the nominal stress method seems unsuitable for describing the fatigue strength of thin welded structures with varying initial distortion.

In terms of structural stress, the difference between small- and full-scale specimens is very small and the fatigue strength is considerably higher than the IIW structural stress design curve FAT100 [3], see Figs. 17 and 18. As varying initial distortions are
The structural hot spot stress is able to describe the fatigue strength of thin structures. For small-scale specimens, the fatigue strength at 2 million load cycles with the survival probability of 97.7% is 217 MPa. The slope of the S-N curve is $m = 4.9$ and the scatter range index $1:T_r = 1:(FAT_{10\%}/FAT_{90\%})$, defined by the ratio between the fatigue strength at 2 million load cycles at 10% and 90% of survival probability, is 1:1.13. For full-scale specimens, the values are presented at two separate locations, one at the section where highest normal strain occurred in the panel FE model (Fig. 17) and one at the actual crack initiation location (Fig. 18), see also Fig. 13 and Table A.2. The difference between these two approaches is very small, FAT = 220 MPa, $m = 5.3$ and $1:T_r = 1:1.23$ for maximum strain location, i.e. the estimated crack initiation location, and FAT = 206 MPa, $m = 4.7$ and $1:T_r = 1:1.22$ for actual crack initiation location.

The summary of the fatigue test results for small- and full-scale specimen series is given in Table 4. For each specimen separately the applied maximum and minimum load, nominal and structural stress range, number of cycles and crack initiation location is provided in Appendix A.

4. Discussion

The fatigue strength of 4-mm thick laser-hybrid welded cruise ship decks was studied experimentally for the first time using small- and full-scale specimens cut from the same panels. Comprehensive geometry measurements were carried out and the results were utilized in FE-model creation. The initial distortions close to butt weld were approximately 3–4 times smaller than in previously reported thin arc welded navy vessel decks [6]. Despite the smaller amount of distortion, the shape was relatively sharp around the butt weld, resulting in significant effect on structural stress. The comparison of normal strains from FE-analysis and experiments showed very good agreement, indicating proper consideration of initial distortions. Also the crack initiation locations were in line with the prediction, which was not always the case for panels in [6].

The fatigue strength was evaluated using nominal and structural hot spot stress approach [3]. Because of the large variation of initial distortion in thin plate structures, the definition of the fatigue strength and S-N curve slope is difficult in nominal stress system. This agrees with the earlier observations for thin small-scale specimens [5] and panels [6]. When structural hot spot stress approach is applied, the fatigue strength is at the same level, the scatter is small and the slope is close to $m = 5$ for both small- and full-scale specimens. The scatter is much smaller than previously reported for thin plates in e.g. [15]. In addition, the fatigue strength is considerably higher in comparison to thin arc welded panels in [6] and IIW structural stress design curve FAT100 [3]. This means firstly that hot spot stress can better describe the fatigue strength of thin welded structures and secondly that high fatigue strength can also be achieved in full-scale structures. However, in order to achieve similar or higher fatigue capacity as with thick plates, the magnitude and the shape of the initial distortion as well as the weld quality need to be controlled. The minor stabilized compressive residual stresses close to fatigue critical butt joint may also have increased the fatigue strength slightly as explained in [25]. However, this effect is similar for both small- and full-scale specimens.

It must be noted that the number of cycles to failure was defined at the final fracture for both small- and full-scale specimens. Visible macro crack was present at the very end of the lifetime for both small- and full-scale specimens, which seems to be different from the observations made for thicker plates in [26–28]. The fracture surfaces have several crack initiation locations, which is typical for high quality welds. This indicates that the propagation time from through-thickness crack to final fracture has been short. Therefore, it can be assumed that the difference in propagation time between small- and full-scale specimens was small. However, more comprehensive analysis is needed in order to make solid conclusions on the crack growth behavior of thin full-scale specimens. Also, small-scale specimens were tested at
the load ratio $R = 0$, while panels at $R = 0.1$, which is unfavorable for the latter.

5. Conclusions

From the fatigue strength investigation of 4-mm thick laser-hybrid welded structures, following conclusions can be drawn:

- The amount of initial distortion is smaller in comparison to shorter arc welded panels reported earlier in [6]. The distortion shape close to butt weld has significant influence on the structural stress.
- If initial distortion and geometrical nonlinearity are properly considered in the analysis, the FE results agree exceptionally well with the experiments. The FE procedure was described in this paper.
- Nominal stress approach is not suitable for thin welded structures due to large variation of initial distortion.
- In terms of structural stress the full- and small-scale specimens have equal fatigue strength with small scatter and slope of S-N curve close to $m = 5$. In addition, the measured fatigue strength is considerably higher in comparison to IIW structural stress design curve FAT100.

The future work should include establishing the modeling approach suitable for large thin structures, including detailed guideline for FE-analysis and model preparation. For similar or higher fatigue capacity in comparison to thicker plates, both the magnitude and the shape of initial distortion needs to be controlled and appropriate limits established. Also the effect of weld quality on the fatigue strength should be better understood by applying advanced fatigue characterization methods adjusted for thin plates [8]. Finally, the effect of variable amplitude loading should also be investigated.

Acknowledgements

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Appendix A

The applied maximum ($F_{\text{max}}$) and minimum force ($F_{\text{min}}$), nominal ($\Delta\sigma_{\text{nom}}$) and structural hot spot stress range ($\Delta\sigma_{\text{HS}}$), number of cycles to failure ($N_f$) and crack initiation locations are provided in Table A.1 for all small-scale specimens and in Table A.2 for full-scale specimens.

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijfatigue.2016.11.012.

Table A.1
Fatigue test results for all small-scale specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$F_{\text{max}}$, N</th>
<th>$F_{\text{min}}$, N</th>
<th>$\Delta\sigma_{\text{nom}}$, MPa</th>
<th>$\Delta\sigma_{\text{HS}}$, MPa</th>
<th>$N_f$</th>
<th>Crack init. location</th>
</tr>
</thead>
<tbody>
<tr>
<td>B4.HY.1</td>
<td>16,737</td>
<td>154</td>
<td>207</td>
<td>336</td>
<td>441,558</td>
<td>Root, right</td>
</tr>
<tr>
<td>B4.HY.2</td>
<td>14,928</td>
<td>153</td>
<td>185</td>
<td>288</td>
<td>2,000,000</td>
<td>Runout</td>
</tr>
<tr>
<td>B4.HY.3</td>
<td>19,198</td>
<td>167.5</td>
<td>238</td>
<td>433</td>
<td>117,345</td>
<td>Root, left</td>
</tr>
<tr>
<td>B4.HY.4</td>
<td>14,126</td>
<td>149</td>
<td>175</td>
<td>323</td>
<td>399,636</td>
<td>Root, right</td>
</tr>
<tr>
<td>B4.HY.5</td>
<td>15,904</td>
<td>126</td>
<td>197</td>
<td>368</td>
<td>287,013</td>
<td>Root, right</td>
</tr>
<tr>
<td>B4.HY.6</td>
<td>13,496</td>
<td>130.2</td>
<td>167</td>
<td>312</td>
<td>781,767</td>
<td>Root, right</td>
</tr>
<tr>
<td>B4.HY.7</td>
<td>17,280</td>
<td>140</td>
<td>214</td>
<td>388</td>
<td>194,707</td>
<td>Root, right</td>
</tr>
<tr>
<td>B4.HY.8</td>
<td>16,143</td>
<td>176</td>
<td>200</td>
<td>329</td>
<td>480,786</td>
<td>Root, right</td>
</tr>
<tr>
<td>B4.HY.9</td>
<td>16,621</td>
<td>167</td>
<td>204</td>
<td>308</td>
<td>644,124</td>
<td>Root, right</td>
</tr>
<tr>
<td>B4.HY.10</td>
<td>7713</td>
<td>124</td>
<td>95</td>
<td>296</td>
<td>556,720</td>
<td>Root, left</td>
</tr>
<tr>
<td>B4.HY.11</td>
<td>10,500</td>
<td>159</td>
<td>129</td>
<td>288</td>
<td>496,713</td>
<td>Root, left</td>
</tr>
</tbody>
</table>

* Nominal stress range is calculated assuming cross sectional area of $20 \times 4 = 80$ mm$^2$.

Table A.2
Fatigue test results for all full-scale specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$F_{\text{max}}$, kN</th>
<th>$F_{\text{min}}$, kN</th>
<th>$\Delta\sigma_{\text{nom}}$, MPa</th>
<th>$\Delta\sigma_{\text{HS}}$, MPa</th>
<th>$N_f$</th>
<th>Crack init. location/ early growth location</th>
<th>Max strain location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 121</td>
<td>650</td>
<td>65</td>
<td>179</td>
<td>430</td>
<td>139,124</td>
<td>Root, y+, x+ plate edge</td>
<td>x+ plate edge</td>
</tr>
<tr>
<td>Panel 143</td>
<td>600</td>
<td>60</td>
<td>166</td>
<td>480</td>
<td>72,400</td>
<td>Root, y+, x = 250...300 and 340...410 mm</td>
<td>x = 284 mm</td>
</tr>
<tr>
<td>Panel 165</td>
<td>620</td>
<td>62</td>
<td>171</td>
<td>461</td>
<td>151,795</td>
<td>Root, y+, x = 190...230 mm</td>
<td>x = 195 mm</td>
</tr>
<tr>
<td>Panel 221</td>
<td>600</td>
<td>60</td>
<td>166</td>
<td>340</td>
<td>291,858</td>
<td>Root, y, x = 340...345 mm</td>
<td>x = 275 mm</td>
</tr>
<tr>
<td>Panel 234</td>
<td>520</td>
<td>52</td>
<td>144</td>
<td>329</td>
<td>517,655</td>
<td>Root, y, x = 300...350 mm</td>
<td>x = 280 mm</td>
</tr>
<tr>
<td>Panel 256</td>
<td>450</td>
<td>45</td>
<td>124</td>
<td>347</td>
<td>539,686</td>
<td>Root, y, x = 330...420 mm</td>
<td>x = 351 mm</td>
</tr>
<tr>
<td>Panel 312</td>
<td>650</td>
<td>65</td>
<td>179</td>
<td>399</td>
<td>370,868</td>
<td>Root, y, x = plate edge</td>
<td>x = 280 mm</td>
</tr>
<tr>
<td>Panel 334</td>
<td>620</td>
<td>62</td>
<td>171</td>
<td>319</td>
<td>529,996</td>
<td>Root, y, x = 325 mm</td>
<td>x = 320 mm</td>
</tr>
<tr>
<td>Panel 356</td>
<td>655</td>
<td>65</td>
<td>181</td>
<td>342</td>
<td>239,108</td>
<td>Root, y, x = 160...170 (y-) &amp; proportionally other side (y+)</td>
<td>x = 310 mm</td>
</tr>
</tbody>
</table>

* Nominal stress range is calculated assuming cross sectional area of $545 \times 4 + 2 + 540 = 3260$ mm$^2$. 


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References


