Structural performance of laser welded edge joints made of high-strength steel

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Abstract. Laser welding is a widely-used fusion welding process in industry. However, laser welding is not a common welding process in the manufacture of industrial crane structures. There has been a remarkable increase in the available strength classes of steel grades over the last 10 years, such that strengths of up to 1200 MPa are now commercially available. This enables the use of thinner materials in welded products and at the same time, has opened up new possibilities for using laser welding more widely in the manufacture of steel structures. This study focuses on the static and fatigue strength of the laser-welded joints. Details investigated are edge joint with flange preparation between two rectangular tubes and edge joint between flat bar and rectangular tube. A novel fatigue strength assessment concept, the FATmod method, is applied to assess the theoretical fatigue performance of the joint in comparison with the effective notch stress method with a FAT630 design curve. The FATmod method is based on the local stress ratio at a fatigue-critical point of the joint and the analysis considers the strength of the material, surface quality and applied stress ratio in the assessment of fatigue. The study shows that the samples failed from the base material side in static tests and the FATmod method developed was found to agree well with the test results.

1. Introduction

Laser welding is a widely-used fusion welding processes in various industrial applications. However, laser welding is not a common welding process in the manufacturing of industrial crane structures. The most frequently-used processes are submerged arc welding (SAW) and gas metal arc welding (GMAW). There has been a remarkable increase in the available strength classes of steel grades over the last decade and strengths of up to 1200 MPa are now commercially available. This has enabled the use of thinner materials in welded structures and consequently, has opened up wider possibilities of utilizing the laser-welding process in the fabrication of steel structures. This has provided not only a change in plate thickness but typically, has stimulated the whole construction process with fresh ideas on how to produce the required performance of the crane. This investigation focuses on the static and fatigue strength of laser welds. The details investigated are edge joint with flange preparation I-type joint between two rectangular tubes and edge joint between flat bar and rectangular tube.
2. Experimental tests

2.1. Test specimens

Two different specimen configurations were used in this study: the first test specimen type consisted of
a rectangular hollow section with flat bar and the second consisted of two rectangular hollow sections
welded together. The thickness of the flat bars was 25 mm and the steel grade used was normal
construction steel S355J2. The rectangular hollow sections were manufactured using a laser-welding
process. The material thickness of the rectangular profile was 3 mm and the steel was direct quenched
steel S900. Fig. 1 shows the main dimensions of the test samples and the nominal material properties
from the literature are shown in Table 1. The conventional carbon equivalent values (CEV) and the other
carbon equivalents (PL) for laser weld were calculated [1]. The maximum carbon equivalent values
available from steel suppliers are shown in Table 2.

Table 1. Chemical compositions [ % ] of used steel [1] [2] [3]

|        | C    | Mn  | Cr | Mo | V | Cu | Ni | S    | Si | P    | B    |
|--------|------|-----|----|----|---|----|----|------|----|------|------|
| S355J2 | 0.2  | 1.6 | 0  | 0  | 0 | 0  | 0  | 0.025| 0.025| 0.025| 0    |
| Optim900QC | 0.20 | 1.6 | 0.8| 0.7| 0 | 0.3| 2  | 0.01 | 0.05 | 0.03 | 0    |

Table 2. Mechanical properties of used steel. [3] [4]

|        | $f_y$ [MPa] | $f_u$ [MPa] | $A_s$ [MPa] | CEV/CEVmax | LP |
|--------|-------------|-------------|-------------|-------------|----|
| S355J2 | 355         | 460         | 23          | 0.47/0.45   | 0.27|
| Optim 900 QC | 900 | 950         | 7           | 0.92/0.58   | 0.27|

The test pieces were 100 mm long and were cut from longer sections, about 1000 mm long see Fig. 1.
All welds were produced without filler material.

Fig. 1. The shape and main dimensions of the test samples. a) laser weld joint between S355J2
rectangular profile and HS-steel profile and b) laser weld joint between two HS-steel hollow-profile.
(red arrows show laser-weld seam positions; thickness of part 1 is 3 mm and part 2 is 20 mm; width of
part 2 is 200 mm)
The welding processes was carried out using a CO2-laser welding machine. The welding power was 4.4 kW and welding speed was ether 1.50 m/min or 2.50 m/min. The average width of the weld was about 0.9 mm and penetration $s_w$ was about 4.7 mm in edge joint seams; see Fig. 1. The laser machine type used was a CO2-Laser Rofin Sinar 4.5 kW and the shielding gas used was helium. Gas flow was 10 l/min. All weldings were performed at normal room temperature of about 20 °C without preheating the welding. The welding parameters are seen in Table 3. Focus = 0 means the laser beam was adjusted so that its focal point was on the surface of test specimen.

Table 3. Used welding parameters and approximation of heat input values $Q$.

| Joint                  | Focus [mm] | Power [kW] | Speed [mm/min] | Gas                  | $Q$ [kJ/mm] |
|------------------------|------------|------------|----------------|----------------------|-------------|
| Plate and O-profile    | 0          | 4.4        | 2500           | Helium/10 l/min      | 0.07        |
| Two O-profiles joint   | 0          | 4.4        | 2500           | Helium/10 l/min      | 0.07        |
| Lap joint              | 4.4        | 1500       | Helium/10 l/min| 0.12                 |

Heat input values $Q$ were calculated based on Eq.(1) that is given in standard SFS-EN 1011-1

$$Q = k \cdot \frac{P}{v} \cdot 1000$$

where $k$ is thermal coefficient, $P$ is power [W] and $v$ is welding speed [mm/s]. The Eq. (1) gives results in unit kJ/mm. The thermal coefficient, which SSAB proposed to use for laser weld [5], was selected 0.7.

2.2. Static tensile tests

In order to validate the ultimate performance of the structure, static tests were carried out. The tensile test setup is presented in Fig. 2. The samples were clamped to the table of the test ring and external force was applied to the test pieces through the rigid yoke.

There were six tensile tests in total. The tensile strength results and typical failure modes are shown in Fig. 3. The average depth $s_w$ of the laser-weld seams was about 4 mm. The ultimate load carrying capacity was 139 kN for sample A and 114 kN for sample B, respectively. The rupture location was at the weld toe outer side of the beam and the fracture passed perpendicularly through the wall thickness of the base material. The nominal tensile capacity of the webs of the hollow profile is 540 kN ($f_y \cdot$area). This means that the capacity of the formed and welded area related to the capacity of the webs is 0.26 for sample A and 0.21 for sample B.
Fatigue tests were carried out in the steel structures laboratory at LUT University. The tests were performed using constant amplitude loading, and the stress ratio $R$ was set at close to 0.1, as shown in Table 4. The test matrix and test results are presented in Table 4. The nominal membrane stress range in the webs, equal to $F / A_w$, is presented in Table 4. The reference area used is $A_w = 600 \text{ mm}^2$.

The locations of the fatigue failures are shown in Fig. 2. Point 1 illustrates the crack through the base material, Point 2 the crack at the weld toe propagating in the base material and Point 3 the crack at weld root propagating in the base material, respectively.

| Sample | $F_{\text{max}} / F_{\text{min}}$ [kN] | $R$ [-] | $\Delta \sigma$ at web [MPa] | $N_f$ [cycles] | Failure |
|--------|---------------------------------|--------|-------------------------------|---------------|---------|
| A-KO_4 | 10.40 / 0.20                    | 0.02   | 17.1                          | 102000        | Point 1, at end of profile |
| A-KO_5 | 35.66 / 0.20                    | 0.01   | 59.1                          | 1438          | Point 1, at end of profile |
| A-KO_6 | 9.93 / 0.20                     | 0.02   | 16.2                          | 25440         | Point 1, at end of profile |
| A-KO_7 | 15.30 / 5.00                    | 0.33   | 17.2                          | 63452         | Point 1, at end of profile |
| A-KO_8 | 12.06 / 0.00                    | 0.00   | 20.1                          | 13920         | Point 1, at end of profile |
| A-KO_9 | 12.35 / 0.31                    | 0.03   | 20.1                          | 13560         | Point 1, at end of profile |
| A-KO_12| 93.13 / 0.85                    | 0.01   | 153.8                         | 180           | Point 1, at end of profile |
| B-KOA1_1| 10.34 / 0.17                   | 0.02   | 16.9                          | 139962        | Point 1, at end of profile |
| B-KOA1_2| 10.28 / 0.24                   | 0.02   | 16.7                          | 129686        | Point 1, at end of profile |
| B-KOA1_3| 10.34 / 0.28                   | 0.03   | 16.8                          | 122854        | Point 1, at end of profile |
| B-KOA1_4| 12.36 / 0.25                   | 0.02   | 20.2                          | 36478         | Point 1, at end of profile |
| B-KOA1_5| 12.35 / 0.24                   | 0.02   | 20.2                          | 34730         | Point 1, at end of profile |
| B-KOA1_6| 12.50 / 0.39                   | 0.03   | 20.2                          | 91500         | Point 1, at end of profile |
| B-KOA1_7| 12.17 / 0.20                   | 0.02   | 19.9                          | 71492         | Point 1, at end of profile |

The depth of the weld seams was measured after the failure for four test samples. The selected samples were assumed to present a typical cross section of weld seam shapes, and two joints were investigated in detail, as illustrated in Figure 7. The measured mean penetration $s_w$ was 4 mm for sample A and 4.55 mm for sample B. These values were subsequently used in this investigation and are slightly different than the values obtained from the test samples used in the static tests.
3. FE-models

The linear-elastic stress concentration factors $K_t$ are needed in fatigue strength assessment of the joints using the notch stress concepts. These were determined with the FE method at both the weld toe and weld root sides of the laser weld in the flange groove. Parabolic tetra elements were used. The effective notch stress approach was applied and a fictitious notch radius of $r = 0.05$ mm was applied in the model in accordance with the recommendations for a thin-walled joint ($t < 5$ mm) [6]. Six elements over the 45-degree arc were used in the models, fulfilling the mesh density requirement proposed by Fricke [7].

Double symmetry was exploited and a linear material model was used. Young’s modulus $E = 210000$ MPa and Poisson ratio $\nu = 0.3$ were used. The gap between connected palates was assumed to be zero, and no contact configuration was applied to this gap.

The external tensile force was applied to the models through a yoke and the value of the force was 3750 N in one quarter FE model. The yoke was connected to the rectangular hollow section using a contact boundary condition. The friction value was set to be 0.2 in this contact area. The measured average values for weld dimensions were used in FEA. Fig. 5 presents the mesh and boundary conditions used in FEA.

The stress concentration factors were calculated in three different locations. The factors $K_{t,w,t}$ and $K_{t,w,r}$ were calculated based on stress distribution through the weld seam, while the stress concentration factor $K_{t,b,t}$ was determined based on stress distribution through the plate thickness at the boundary line between the weld and the base plate, corresponding to the potential fatigue failure paths in the studied laser welds. The calculated stress distributions $\sigma(x)$ were divided in membrane-, bending- and non-linear stress components, as shown in Fig. 5. Separation was carried out by applying the widely-used Eqs presented in reference [8].

Linear-elastic notch stress concentration factors were calculated using the following formula

$$K_t = \frac{\sigma_{mem} + \sigma_{bend} + \sigma_{nlp}}{\sigma_{mem} + \sigma_{bend}}$$

The stress components and absolute stress concentration factors are given in Table 5. Stresses were calculated with external force 3750 N in test setup.

Table 5. Selected stresses and the stress concentration values. $K_t$. Membrane stress component is compress, because the yoke does not be rigid and external force effects on the middle of the yoke.

| $K_{t,w,t}$ | $K_{t,w,r}$ | $K_{t,b,t}$ | Stress path (see Fig. 8) |
|------------|------------|------------|-------------------------|
| -69        | -69        | -14        | sample A, Line 1        |
| 143        | -143       | 515        | sample A, Line 1        |
| 1112       | 1002       | 1775       | sample A, Line 2        |
| 16.0       | 3.7        | 4.5        | sample A, Line 2        |
| -120       | -120       | -28        | sample B, Line 1        |
| 42         | -42        | 491        | sample B, Line 1        |
| 1161       | -552       | 1159       | sample B, Line 2        |
| 13.9       | 4.4        | 3.5        | sample B, Line 2        |
Fig. 5. The type of test samples and detail of mesh in FE models that were used in the determination of stress concentration factors. Lines 1 and 2 show the stress plotting lines that were used in subsequent calculations. The stresses were read in nodes on the outer surface part. Example stress distribution from line 1 and stress components (x is distance from critical point).

4. Fatigue strength assessment of the joints

4.1. Modified notch stress approach

The fatigue strength of laser-welded joints is evaluated by means of a modified local stress approach, with reference to Nykänen et al. [9] [10] [11], Björk et al. [12] and Peippo et al. [13].

The linear-elastic stresses and strains were transformed to elastic-plastic ($\sigma_1$, $\varepsilon_1$) components by using Eq. (5)

$$
\varepsilon_1 \cdot \sigma_1 = \left(\frac{K_{f,mod} \cdot \sigma_{nom,max} + \sigma_r}{E}\right)^2 \rightarrow \text{output } \sigma_1 \text{ and } \varepsilon_1
$$

(3)

where $\sigma_{nom,max}$ is the maximum nominal stress, $\sigma_r$ is residual stress, $E$ is Young’s modulus, $n'$ is the cyclic strain hardening exponent, and $K'$ is the cyclic strength coefficient. In this investigation $n'$ is 0.164 and $K' = 1.65 \cdot f_u$ [14]. $K_{f,mod}$ is a notch-sensitive factor, that is calculated according to Eq. (6). The effect on surface quality is taken into account in Eq. (6) through the term $C_{str}$, that is, the roughness correction factor for axial stress. Factor $C_{str}$ is calculated using Eq. (7).

$$
K_{f,mod} = (K_f + \frac{1}{C_{str}} - 1)
$$

(4)

$$
C_{str} = 1 - a_R \cdot \log(R) \cdot \log(\frac{2 \cdot f_u}{S_{\mu,min}})
$$

(5)

where $a_R$ is a roughness constant (for steel $a_R$ is 0.22), $S_{\mu,min}$ is minimum ultimate tensile strength (for all structural steel $S_{\mu,min} = 400$ MPa [15]), $R$ is the roughness value of the surface in [$\mu$m] and $f_u$ is the ultimate strength of the material.
Elastic-plastic stress and strain ranges are calculated (Δσ, Δε) by using Eq. (8). This equation is based on Neuber’s rule and kinematic hardening rules

$$\Delta \varepsilon \cdot \Delta \sigma = \left(\frac{K_{f_{\text{mod}}} \cdot \Delta \sigma_{\text{nom}}}{E}\right)^2$$

$$\Delta \sigma = \Delta \sigma_{\text{nom}} + 2 \left(\frac{\Delta \sigma}{2 \cdot K'}\right)^{1/n'}$$

(6)

where Δσ_{nom} is nominal stress range in the location under investigation. True stress ratio R_{true} is calculated by the equation (9). The stress ratio R_{true} values were limited between -2 to 0.5.

$$\sigma_2 = \sigma_1 - \Delta \sigma$$

$$R_{true} = \min(\sigma_3, \sigma_2) \rightarrow \text{output } \sigma_2 \text{ and } R_{true}$$

(7)

All stresses are commeasured into a reference stress system, corresponding to the true stress ratio of R_{true} = 0. A Smith-Watson-Topper (SWT) mean stress correction is applied to define a new stress range Δσ_{ref,R=0} referring the equivalent stress range, when R = 0, according to Eq. (10)

$$\Delta \sigma_{r_{\text{ef,R=0}}} = \frac{K_{f_{\text{mod}}} \cdot \Delta \sigma_{\text{nom}}}{\sqrt{1 - R_{true}}}$$

(8)

4.2. Stress ranges

The fatigue test results are tabulated in Table 6 and the stress ranges calculated using the linear stress concentration factor are given in Table 5. Thus, the linear stress calculation equations can be carried out according to Eqs. (9) – (11).

$$\Delta \sigma_1 = K_{t,b,1,0} \cdot \Delta \sigma_{\text{nom}}$$

$$\Delta \sigma_2 = K_{t,w,t} \cdot \Delta \sigma_{\text{nom}}$$

$$\Delta \sigma_3 = K_{t,w,r} \cdot \Delta \sigma_{\text{nom}}$$

(9)\hspace{1cm}(10)\hspace{1cm}(11)

The stress range is calculated using Eq. (12). The calculated stress range can be positive or negative depending on the stress component values.

$$\Delta \sigma_{\text{nom}} = \sigma_1 - \sigma_2$$

(12)

| Test sample | Point 1 | Point 2 | Point 3 | Nf [cycles] | Failure location | Test sample | Point 1 | Point 2 | Point 3 | Nf [cycles] | Failure location |
|-------------|---------|---------|---------|-------------|-----------------|-------------|---------|---------|---------|-------------|-----------------|
| A-KO 4      | 1553    | 811     | -829    | 102000      | Point 1         | B-KOA1_1    | 1099    | -733    | -848    | 139962      | Point 1         |
| A-KO 5      | 5374    | 2804    | -2869   | 1438        | Point 1         | B-KOA1_2    | 1085    | -724    | -478    | 129686      | Point 1         |
| A-KO 6      | 1475    | 770     | -788    | 25440       | Point 1         | B-KOA1_3    | 1087    | -725    | -479    | 122854      | Point 1         |
| A-KO 7      | 1562    | 815     | -834    | 63452       | Point 1         | B-KOA1_4    | 1309    | -874    | -577    | 36478       | Point 1         |
| A-KO 8      | 1826    | 953     | -975    | 13920       | Point 1         | B-KOA1_5    | 1308    | -874    | -577    | 34730       | Point 1         |
| A-KO 9      | 1826    | 953     | -975    | 13560       | Point 1         | B-KOA1_6    | 1308    | -874    | -577    | 91500       | Point 1         |
| A-KO 12     | 13992   | 7302    | -7470   | 180         | Point 1         | B-KOA1_7    | 1293    | -863    | -570    | 71492       | Point 1         |

4.3. Modified fatigue strength FAT_{mod} using the reference stress ratio

The mean FAT_{m} classes were calculated for Point 1, where the fatigue failures occurred. The reference stress component Δσ_{ref,R=0} is used in regression analyses. The slope of the S-N curve is set to be m = 3. For comparison, the regression analyses were also conducted by using free slope S-N curves. The calculated mean reference FAT_{m,Rtrue=0} and characteristic FAT_{c,Rtrue=0} values are given in Table 7 and the S-N curves are plotted in Fig. 7. In the calculations it was assumed that no residual stresses exist and that surface quality R_{c} = 100 (the surface quality was only an estimate).
The effect on the residual stress assumption to deviation value in regression analyses is estimated in Fig. 11. The value of the residual stress was varied in relation to material yield strength, initial residual stress values were calculated with Eq. (13), and the results were applied in Eq. (5).

\[ \sigma_r = f \cdot f_y, \]  

where \( f \) is scaling factor that vary from -1 to 1 with interval 0.2.

The minimum deviation was given with the residual stress assumption that \( f \) is -0.4, as shown in Fig. 6. The regression analyses were repeated using that initial residual stress assumption. The results are given in Table 7 and in Fig. 7.

![Deviation vs. residual stress assumption in regression analyses.](image)

Factor \( f \), Residual stress \( \sigma_r = f \cdot f_y \)

Table 7. Reference FAT-classes and deviations.

| Test sample | Residual stress | Location | \( m_{\text{fixed}} \) | \( FAT_{m,Rtrue=0} \) and deviation | \( FAT_{c,Rtrue=0} \) and deviation | \( m_{\text{free}} \) | \( FAT_{m,Rtrue=0} \) and deviation | \( FAT_{c,Rtrue=0} \) and deviation |
|-------------|----------------|----------|-----------------|-------------------------------------|-------------------------------------|----------------|-------------------------------------|-------------------------------------|
| A+B         | 0              | Line 1   | 3               | 137                                 | 53                                  | 2.9           | 131                                 | 49.0                                 |
| A+B         | -0.4 \( f_y \) | Line 1   | 3               | 107.7                               | 58                                  | 2.5           | 83.2                                 | 44.8                                 |

The comparison between fatigue test results and calculated fatigue life estimations were given in Fig. 8. The residual stress assumption was varied between 0 (A) and -0.4\( f_y \) (B). Residual stresses were calculated by using the smallest yield strength of the detail. Dotted lines were plotted by using 95% confidential level.

![S-N-curve based assumption of non-existing residual stresses and residual stress assumption - 0.4\( f_y \), and surface roughness of \( R_z \)=100.](image)
4.4. Comparison of the modified fatigue strength $\text{FAT}_{\text{mod}}$ and effective notch stress methods

The effective notch stress method gives a constant FAT class of 630 MPa, when the effective notch radius is 0.05 mm [7]. Linear notch stress is used and the slope of the SN-curve is $m = 3$. Fatigue life predictions generated using ENS and $\text{FAT}_{\text{mod}}$ methods are presented in comparison with the test results in Fig. 9. Calculated lives were obtained with the characteristic values. Results show that the ENS results are unconservative (below the black line of the constant) while $\text{FAT}_{\text{mod}}$ results are conservative (located above the black line). Furthermore, it is worth mentioning that the $\text{FAT}_{\text{mod}}$ method is able to predict, for example, the effect of different parameters, such as applied stress ratio, see Eq. (5), on fatigue strength, and thus enabling more accurate estimations of fatigue life.

5. Conclusion

In this research work static and fatigue experimental tests for laser-welded joints made of normal and ultra high strength structural steels were carried out. The results were compared with numerical values.
obtained through a modified local strain approach. Based on these results the following conclusions can be drawn:

- Nominal static performance of joint compared to capacity of wall thickness in pure tension is rather low, equal to 0.21–0.26 of the web capacity.
- The results indicate that the FATmod method has the capability to describe stress states and it gives a reasonably accurate fatigue time estimation for the details that were investigated. However, the number of test samples was limited and to obtain greater reliability, further tests are needed.
- The fatigue life comparisons indicated that the ENS method with FAT630 (r = 0.05 mm) gives an unconservative fatigue life estimation in comparison with the investigated FATmod method for the laser welds studied.
- Deviation in the statistical analyses was lowest when the residual stress assumption in the equations was equal to $\sigma_r = -0.4f_y$.

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