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Influence of the base material strength and edge preparation on the fatigue strength of the structures made by high and ultra-high strength steels

Risto Laitinen[a], Ilkka Valkonen[b] and Jukka Kömi[a] *

[a]Ruukki Metals Oy, Rautaruukintie 155, FI-92101, Raahe, Finland
[b]Ruukki Metals Oy, Harvialantie 420, FI-13300, Hämeenlinna, Finland

Abstract

In recent years the high and ultra-high strength steels have been developed and applied for light-weight constructions such as the structural members of mobile equipment in order to reduce weight and fabrication costs as well as to contribute to the performance. In many applications, especially in the use of ultra-high strength steels, the welds are tended to locate outside of the highly stressed regions and use the post weld improvement for the critical welds. This means that the non-welded sections are in load-carrying positions and have to take into the consideration in the design of the structures.

Novel test results have shown that the fatigue strength of the base material increases by increasing the yield strength of steel and the maximum fatigue class in the design codes FAT 160 and a slope, m=5, is conservative when the yield strength of steel is equal and higher than 355 N/mm2. Only standard EN 13001-3-1:2012 allows applying for the higher fatigue classes by increasing the yield strength in cranes.

In this paper the fatigue test results from high and ultra-high strength strip rolled steels are presented and compared with the fatigue classes in standard EN 13001-3-1:2012. Also a cross-member brace connection to main chord flange in vehicle chassis is presented as a design example.

Keywords: Fatigue strength; High strength steesl; Base plate; Thermal cut; Surface roughness; Hardness; Residual stress

* Corresponding author. Tel.: +358-20-592-2582; fax:+358-20 -592-3037
E-mail address: risto.laitinen@ruukki.com

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1. Introduction

Increasing demands to reduce weight and manufacturing costs of light-weight constructions such as the structural members of mobile equipment have led to development and use increasingly high and ultra-high strength steels. In main applications the fatigue properties of the base material and the welded joints are the basic criteria in design. Nowadays, the advanced steel manufacturing processes such as thermomechanical rolling integrated with direct quenching make possible to achieve high strength using a lower level of alloying elements. Thus the weld joints tend to soften during welding and should locate outside of the highly stressed region. In addition, the use of the post weld improvement for the most critical welds improves the fatigue properties of the equipment. This means that the non-welded sections are in the highest load-carrying positions and have taken into the considerations in the fatigue design.

The test results have shown that the fatigue strength of the base material increases by increasing the yield strength of steel. In addition to the strength of steel the surface finish has a significant influence on the fatigue strength of the base plate. The base material strength and the residual stresses on the surface have been assumed to dominate in the initiation of fatigue cracks which covers the most significant stage in the fatigue damage of the base plate. On the other hand, the roughness of the plate surface and cut edge have the main factors affecting the fatigue crack propagation especially when larger crack-like defects are present. The investigations have proposed that the fatigue process is controlled by crack initiation up to defect sizes 0.1-0.2 mm with decreasing influence of the base material strength as defect size increases. It has also been found that the surface condition of the as rolled surface was more critical with respect to the fatigue than the thermally cut edges, considering both surface roughness and a positive influence of the residual stresses for the fatigue properties of the thermally cut edges [1].

In the commonly used design codes, the fatigue class FAT 160 with a slope of m=5 is the highest fatigue design strength for the machined edges and FAT 125-140 with a slope of m=3 for the machine thermally cut edges of steel plates [2,3]. The guidelines of the IIW allow to use also higher design stress values if verified by test. Only the general design standard for cranes allows to use higher design stress values for the higher strength steels. The design stress values in tables of this standard take the edge preparation and the surface roughness into account [4].

This paper covers the fatigue test results of high and ultra-high strength strip rolled steels of Ruukki Metals Oy and the corresponding steels presented in the document [1]. The correlation curves of the characteristic values of 95 % survival probability have been presented for the machined, laser cut and plasma cut edges for the different yield strength of steels. The design stress values calculated from the correlation curves have been compared with the design stress values in tables of standard EN 13001-3-1:2012 [4]. Also a cross-member brace connection to main chord flange in vehicle chassis is presented as a design example.

2. Experiments

2.1. Test materials and specimens

The steel materials tested were high and ultra-high strength cold formable steels with a minimum yield strength of 355 MPa up to 1100 MPa manufactured by Ruukki Metals Oy. The plate thicknesses tested varied from 6 to 12 mm. The specified chemical compositions and mechanical properties of the steels are given in Table 1.

Table 1. Chemical composition of steels (wt -%, ladle analysis).

Steel grade	C_{max}	Si_{max}	Mn_{max}	P_{max}	S_{max}	Al_{min}	Ti_{max}
Ruukki Laser 355	0.12	0.03	1.50	0.020	0.015	0.015	-
Ruukki Laser 420	0.12	0.03	1.60	0.020	0.015	0.015	-
Optim 650 MC	0.10	0.20	2.00	0.020	0.010	0.015	0.22
Optim 700 MC	0.10	0.20	2.10	0.020	0.010	0.015	0.22
Optim 900 QC	0.10	0.25	1.15	0.020	0.010	0.015	0.070
Optim 960 QC	0.11	0.25	1.20	0.020	0.010	0.015	0.070
Optim 1100 QC	0.16	0.30	1.25	0.020	0.010	0.015	0.070

In addition, niobium (Nb), vanadium (V), molybdenum (Mo) or boron (B) may be used as alloying elements either singly or in combination

The machined test specimens were prepared at the Research Centre of Ruukki Metals Oy, Raahe. Plasma cutting of the specimens was carried out in the rolling mill of Ruukki Metals, Raahe and at the Technical University of Lappeenranta. Laser cutting of the test specimens was carried out using several CO_2 laser equipment.

2.2. Fatigue tests

All fatigue tests were performed with 250 kN MTS hydraulic testing machine using a testing frequency of 10-20 Hz and a constant amplitude tension loading with R=0.05-0.1. The dimensions of the test specimens are given in Fig. 1. The characteristic fatigue strength values at 2 million cycles were calculated according to the Recommendation of IIW using a slope of m=5 and a survival probability of 95 % [2].

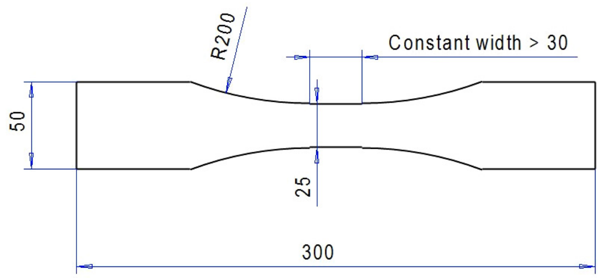


Fig. 1. Dimensions of the test specimens.

2.3. Hardness measurements

Microhardness profile was measured from the laser cut edges of steel grades Optim 900 QC using the Vickers hardness HV0.2.

2.4. Measurement of residual stresses

Residual stresses from the laser cut edge of steel grade Optim 900 QC were measured longitudinally and in the through thickness direction at the Tampere University of Technology using X –ray diffraction method. Positioning of the measurement points in depth were defined by etching.

2.5. Measurement of surface roughness

The surface roughness Rz was measured from the surfaces of the strip rolled plates, machined and thermally cut edges of steel grades with minimum yield strength from 355 to 960 MPa.

3. Test results and discussions

3.1. Influence of the base material strength on the fatigue strength

The characteristic fatigue strength values calculated at 2 million cycles with a slope of m=5 and the equal test results from the research work of Sperle [1] were plotted according to the edge preparation of the specimens and the yield strength of the steel. The trend curves of the test results are given below in Fig. 2 and the trend lines in equations (1)-(3).

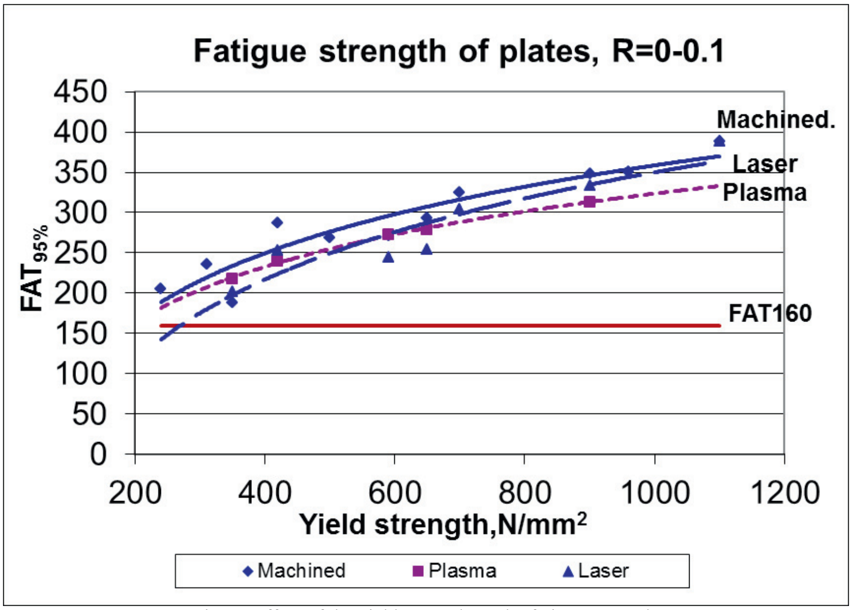


Fig. 2. Effect of the yield strength on the fatigue strength.

$FAT_{95\%}$ (machined)=118.8ln(R_e)-462.11, R^2=0.87 (1)

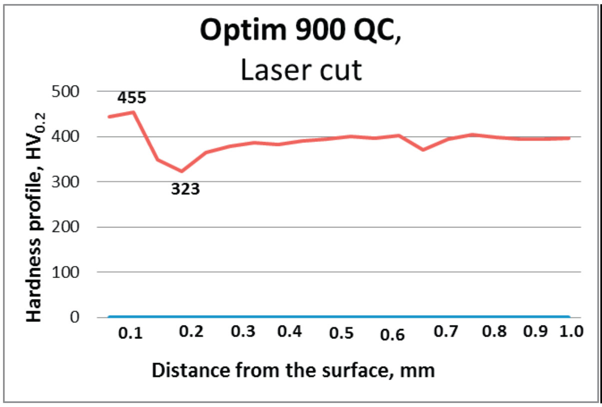
$FAT_{95\%}$ (lasercut)=145.13ln(R_e)-652.61, R^2=0.86 (2)

$FAT_{95\%}$ (plasmacut)=99.21ln(R_e)-361.75, R^2=0.99 (3)

The test results demonstrated predictably that the fatigue strength of the base plate increased by increasing the yield strength. It is noteworthy that the fatigue strength values tested on the laser cut specimens were lower than on the plasma cut specimens when the yield strength was 500 MPa or lower. On the other hand, the fatigue strength of ultra-high strength steels tested on the laser cut specimens was almost the same as that of tested on the machined specimens.

3.2. Hardness profile, microstructural investigations and residual stress measurements

Hardness profile and microstructural investigations demonstrated that the high hardness (max. 455 HV0.2) martensitic microstructure was on the cut surface and a softened zone (min. 323 HV0.2) about 0.2 mm under the surface (Figs. 3-4). Residual stress measurements showed that tensile residual stresses of 150 to 280 MPa were measured longitudinally and compressive residual stresses of -130 to -280 MPa in through thickness direction down to 0.2 mm below the surface and higher tensile residual stresses (max.700 MPa) from 0.2 to 0.4 mm under the cut surface. In generally, hardness and residual stress measurements indicate that tensile residual stresses concentrate on a soft zone about 0.2 mm under the surface enhancing a crack initiation preferably on this zone instead of the hardened surface (Fig. 5).



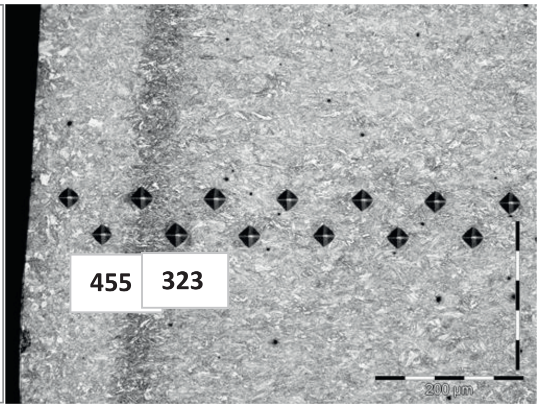


Fig. 3. Microhardness profile of laser cut edge of Optim 900 QC. Fig. 4. Microstructure of the laser cut edge of Optim 900 QC.

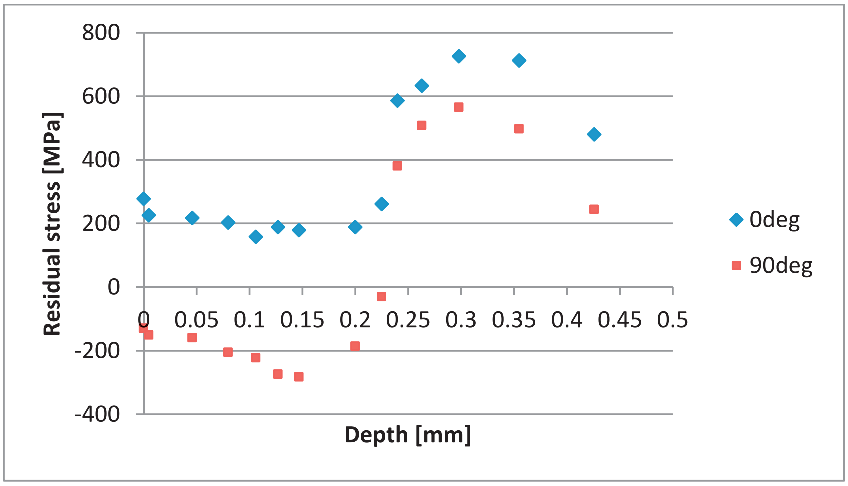


Fig. 5. Residual stresses from the laser cut edge of steel Optim 900 QC (0 deg=longitudinal and 90 deg=through thickness).

3.3. Effect of edge preparation and surface roughness

Surface roughness Rz of the strips and the cut edges were compared with the general values presented by Sperle [1], Table 2.

Table 2. Surface roughness R_z of the strip and cut edges.

	Surface roughness Rz (µm)	
	Test specimens	Document of Sperle [1]
Strip surface	5-20	8-20
Machined edge	1-6	1-20
Laser cut	5-40	9-25
Plasma cut	15-90	10-40

The surface roughness of the test specimens was roughly equal when compared with the test results of Sperle [1], except for a larger scatter of the laser cut specimens due to cutting of the different parameters and equipment.

3.4. Comparison of the test results and the design values in EN 13001-3-1:2012

Table 3. Comparison of test results and the design values in EN 13001-3-1:2012 [4].

	Strip steels			EN 13001-3-1:2012 [4]	
Yield strength f_y (MPa)	Plasma cut Rz=15-90μm	Laser cut Rz=8-20μm	Machined Rz=1-6μm	Thermally cut Rz≤20μm	Machined Rz≤20μm
235	180	125	180	180	200
275	180	140	180	180	200
355	200	180	200	200	225
420	200	200	225	200	225
460	200	200	225	200	225
500	200	200	225	200	225
650	225	225	250	225	250
700	250	250	250	250	280
900	250	280	280	280	280
960	280	280	280	280	315
1100	280	300	300	280	315

The test results showed that the framed fatigue design values specified in EN 13001-3-1:2012 [4] are too high compared with the test results for machined and thermally cut edges in the yield strength classes up to and including 355 MPa and for machined cut edges in the yield strength classes 700 MPa and 960-1100 MPa. The design value of 280 MPa for the thermally cut edge in the yield strength class of 700 MPa was also too high for plasma cut edge due to the higher surface roughness of the test specimen (>20 μm).

The fatigue design values of the strip steels in Table 3 are based on characteristic values at 2000000 cycles and a slope of m=5. However, in utilize of SN curves for fatigue design the whole SN curve should be taken into the consideration. For example in the SN curves of Optim 900 QC steel laser cut specimens characterized a more gently slope of SN curve than machined specimens followed by increase of the characteristic fatigue vales at 2000000 cycles (Figs. 6-7).

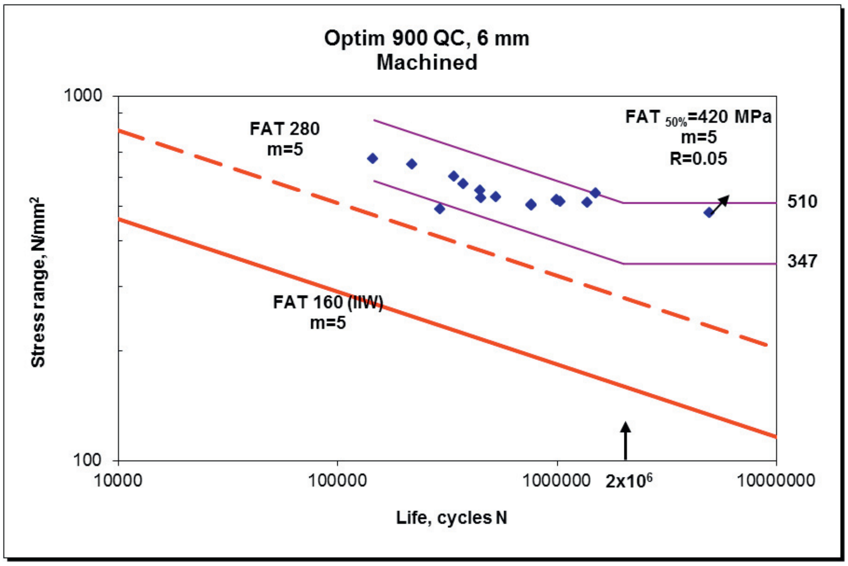


Fig. 6. SN curve defined with the milled Optim 900 QC steel specimens.

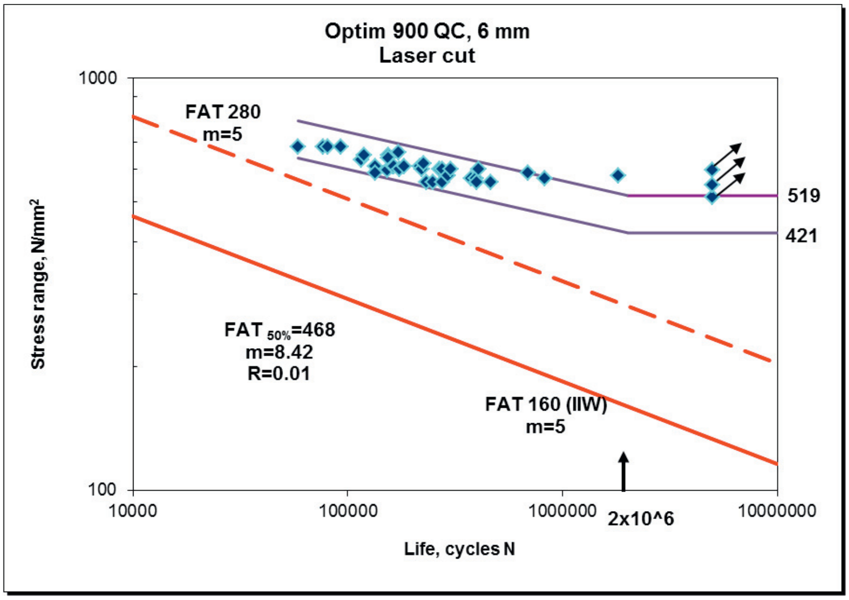


Fig. 7. SN curve defined with the laser cut Optim 900 QC steel specimens.

In many investigations SN curves have been defined in the fatigue range of 40000 to 5 million cycles. However, for example the crane structures need to be designed for higher loads and lower cycles [5]. The fatigue testing of plate material using in the stress control machines is very indefinable in this “low cycle regime” due to a difficult initiation of fatigue cracks without plastic deformation.

4. Design example

As an example two different designs, "a bad design" and "a good design", with the same loads and boundary conditions were analyzed using Code-Aster FEM code to demonstrate the importance of the design and the location of welds.

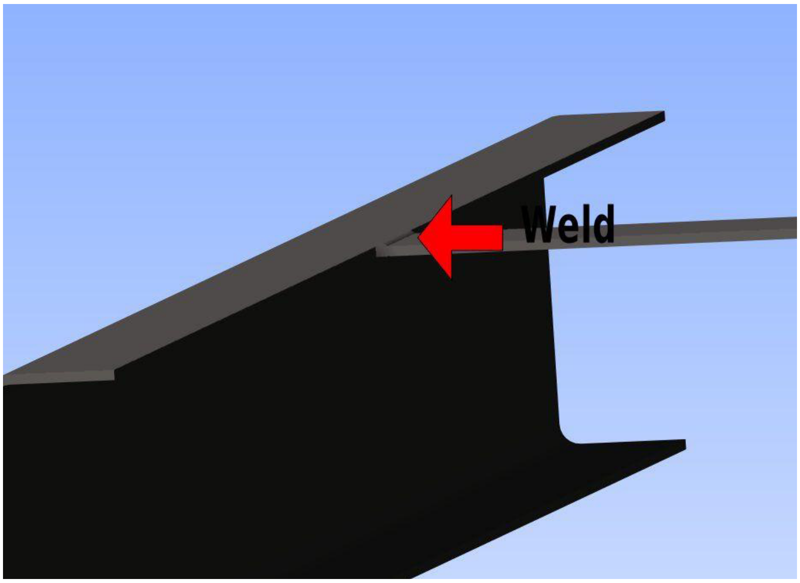


Fig. 8. ”Bad design”.

In "a bad design" a transverse support is fixed with a sharp corner and the result is a high stress peak. Also a weld is in this high stress area. Combination of stress concentration and a weld in the same area can eliminate the advances of using ultra high strength steels (Figs. 8,11).

In "a good design" stress concentrations are reduced by good shapes and positioning of the weld is in a low stress area. Thus good base materials properties of ultra-high strength steels can be utilised (Figs. 9, 12).

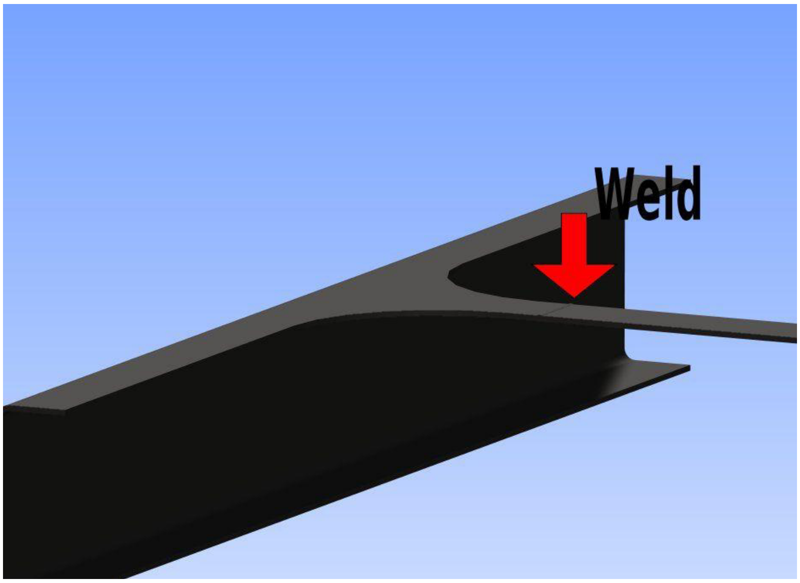


Fig. 9. ”Good design”.

FEM model loading was tension load. Model was symmetrical with 20 node brick elements (Fig. 10).

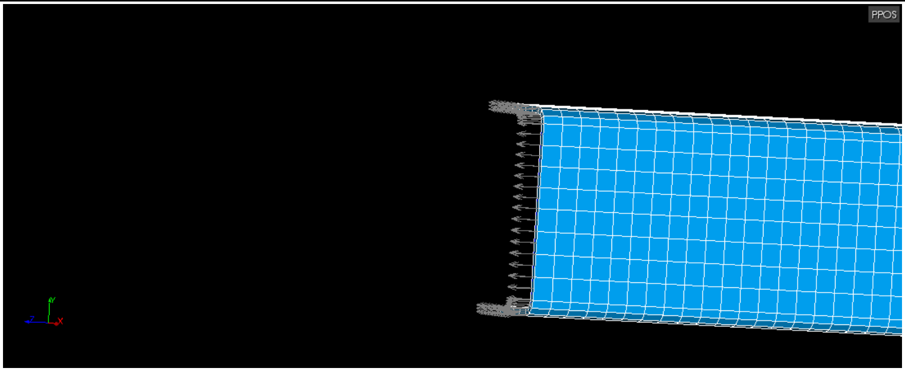


Fig. 10. Loading of FEM model.

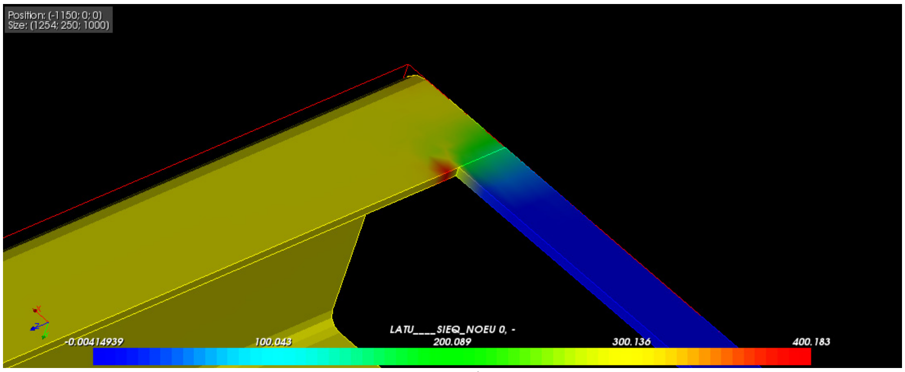


Fig. 11. “Bad design, 1st principal stress”.

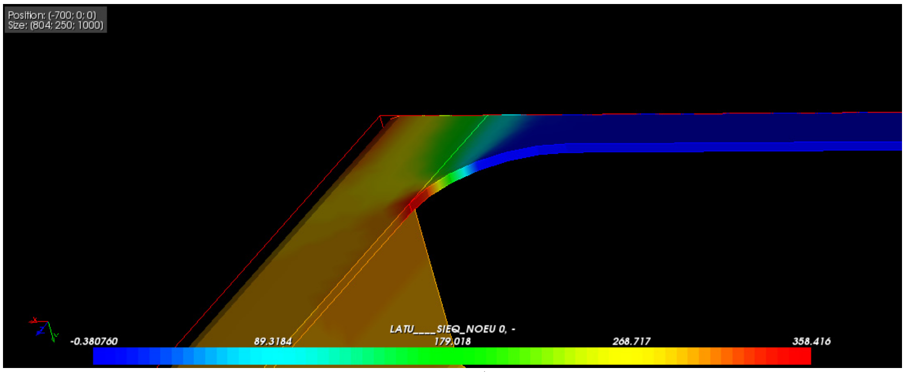


Fig. 12. ”Good design, 1st principal stress”.

5. Conclusions

This investigation covers the fatigue test results from high and ultra-high strength strip rolled steels with the yield strength of 355 MPa up to 1100 MPa and thicknesses from 6 to 12 mm. The fatigue test results on the machined, laser cut and plasma cut specimens together with the corresponding test results from the document [1] were compared with the design values in the design codes.

In the commonly used design codes, the highest fatigue class FAT 160 with a slope of m=5 for machined edges and FAT 125-140 with a slope of m=3 for machine thermally cut edges turned out to be too conservative when the yield strength of steel is equal and higher than 355 MPa as expected.

On the other hand, the highest design values specified for a surface roughness of ≤20 µm in the new crane standard EN 13001-3-1:2012 were too high for steel grades equal and lower than 355 MPa tested with the machined and thermally cut specimens. In addition, the fatigue design values were too high for steel grades 700 MPa, 960 MPa and 1100 MPa when tested with the machined specimens.

The fatigue strength of ultra-high strength steels tested on the laser cut specimens characterized the fatigue strength values close to the ones tested on the machined specimens probably due to tensile residual stress concentration on a soft zone about 0.2 mm under the surface enhancing a crack initiation preferably on this zone instead of the hardened surface.

The design example in this paper evidenced that the high strength of the ultra-high strength steels can be effectively utilized by using a good edge forming for reducing a stress concentration and locating the welds outside of the highly stressed regions.

6. Acknowledgements

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