Fatigue strength of hybrid VHSS-Cast steel welded plates

R.J.M. Pijpers[1,2], M.H. Kolstein[1], A. Romeijn[1]& F.S.K. Bijlaard[1]
[1]Structural and Building Engineering, Delft University of Technology, Delft, the Netherlands

[2]The Materials Innovation Institute (M2i), Delft, the Netherlands

ABSTRACT: Very high strength steels (VHSS) have been made available by the steel industry for many years. In a fatigue loaded VHSS structure absolute and relative stress variation will be higher compared to stresses in structures made of lower grade steels. Cast steel, also available up to yield strength of 1100 MPa, is more and more applied in fatigue loaded bridge and offshore structures. A hybrid connection, consisting of cast steel welded to a rolled steel member, could make the use of VHSS relatively more efficient. If designed properly, cast steel parts could result in welded joints with low stress concentrations, by shifting welds out of the most severe stress location. Small scale fatigue tests on hybrid connections have been executed on a 4-point bending setup in the Stevin II Laboratory of the Delft University of Technology. All plates were made of cast and rolled steels with nominal yield strengths of 460, 690 and 890 MPa, V-welded with thickness 25 mm, in series with and without ceramic backing. The fatigue strength results are evaluated by comparing S-N curves and crack growth curves.

1 INTRODUCTION

1.1 *Very High Strength Steels*

Due to lack of design and fabrication rules Very High Strength Steels (VHSS), with yield strengths of 690 up to 1100 MPa have not found their application in civil engineering structures. Use of VHSS may limit the cross sections of structural members while limiting the weld thickness. However, in a fatigue loaded structure made of VHSS absolute and relative stress variation will be higher compared to stresses in structures made of lower grade steels. Gurney (1979) concluded that the higher the yield strength of base materials the more sensitive the fatigue strength of the material becomes to both the presence of notches and to the surface condition. In case of low notch values notch sensitivity of high strength steel fatigue strength is minimized. The use of VHSS in welded connections requires high fabrication quality and avoidance of large stress concentrations in joints. An effective application of VHSS in civil engineering structures is expected in stiff truss like structures, typically made of Circular Hollow Sections (CHS). If designed properly, use of cast steel parts could result in joints with low stress concentration, while shifting welds out of the most severe stress location. Recent technology makes is possible to make cast steel parts up to yield strength of 1100 MPa, still having a good weldability. The hybrid welded connection between the cast steel member and the CHS as well as the quality requirements of the cast members will be of big importance for the fatigue strength of the joint. Typically, this type of hybrid connections will be welded from the outside of the structural members, resulting in a V-weld shape. Up till now the common steel casting material used in bridge structures is G20Mn5, with 355 MPa yield strength (Herion

2007). In order to investigate the fatigue strength of hybrid connections made of rolled and cast steel with high yield strength, an experimental program has been pointed out within the current study.

1.2 *Fatigue design rules*

For the determination of the fatigue strength of steel structures Eurocode 3 adopts the S-N approach, with detail classifications for various types of connections. The characteristic fatigue strength of transverse butt welds welded from one side is 71 MPa according to EN 1993-1-9 (2005). The use of high strength steel up to S700 is allowed by EN 1993-1-12 (2004). Steels with nominal yield strength higher than 700 MPa are out of the scope of this code. Neither influence of yield strength on the fatigue strength, nor design rules for cast members are included in EN 1993-1-9 (2005). In the design document of the UEG (1985) a procedure is presented to consider the fatigue strength of cast joints in tubular structures. A particular procedure is presented to derive the S-N curve of castings taking account of influence factors for the defect group of the cast member according to ASTM E 446 (1998).

1.3 *Literature evaluation of fatigue experiments on hybrid connections*

For the building of the "Lehrter Bahnhof" in Berlin fatigue tests on welded cast steel plates of 25-40 mm, with and without backing, have been performed by Mang et al. (1999) at constant amplitude, R = 0.1. The steel type used was St52-3 and the cast steel type GS-20Mn5. Also in the tests defective welds were tested. The $\Delta\sigma_{mean}$ (P50%, N=2*10^6) was 112.7 MPa with permanent backing and $\Delta\sigma_{mean}$ =146.1 MPa without use of backing. For the slope of the fatigue strength curve values m =3.9-4.3 were found. Statistical evaluation resulted in a $\Delta\sigma_c$ = 87.5 for the specimens with permanent backing and $\Delta\sigma_c$ = 123.5 for the specimens without backing.

At the EPF Lausanne experimental and numerical work on the fatigue strength of cast steel joints have been carried out (Haldimann-Sturm 2005). In the research initial allowable defect sizes of the cast steel joints were determined next to the fatigue strength of real scale bridge truss girders with K-joints (CHS dimensions chord:244x10; braces: 193.7x8, 193.7x16) made of S355 with GS-20Mn5 cast joints. It was concluded that the fatigue resistance of the welded joints needs to be improved substantially in order to benefit from the high fatigue resistance of the cast nodes. Although defects were not detectable by NDT, all cracks initiated from the weld root. It was found in this research that girth butt welds without backing bars can be classified into detail class 60, $\Delta\sigma_c$ = 60, according to EN 1993-1-9 (2005); the use of backings bars raises the detail class up to $\Delta\sigma_c$ = 90.

The research project "Fatigue of End-To-End CHS Connections" (Puthli et al. 2007) initiated by the University of Karlsruhe is a follow up research on the work performed in Lausanne. It investigates the fatigue resistance of the transition of chord members fabricated in different variations, such as with same inner diameter, same outer diameter, with or without backing plate, misalignment tolerances in combination with cast steel. In the research both axial setup and 4 point bending test setup are used. The research project comprises fatigue experiments on S355 and S460 specimens and corresponding cast steel grade G20Mn5+ QT and G10MnMoV6-3 +QT3 (CHS dimensions: 193.7x20, 298.5x30, 508x55). Results up till now show no remarkable differences between the fatigue strength of S355 and S460 193.7-specimens. All failures started at the root of the welds. With a slope m = 5 a $\Delta\sigma_c$ = 100 seems to be possible. Moreover it is concluded that with a good weld quality a weld backing may be omitted.

2 EXPERIMENTAL PROGRAM

The experimental program of the current study of the Delft University of Technology is split up in two parts: 1) large scale tests series on trusses made of welded circular hollow sections (CHS) and K-joint cast members. 2) small scale test series on V-welded plate connections made of rolled steel and cast steel. Rolled and cast materials used in the large scale tests have similar nominal yield strengths of 690 and 890 MPa. Additionally in the small scale tests plates with nominal yield strength of 460 MPa are tested. The materials to be investigated are cast steels G20Mn5, G10MnMoV6-3 and G18NiMoCr3-6 welded to rolled steels S460, S690 and S890 respectively.

2.1 *Large scale tests; CHS trusses with K-joint cast members*

The geometry of the cast members of the large scale tests is chosen to be similar to the K-joints tested in Lausanne (Haldimann-Sturm 2005). In total two trusses will be tested. The first truss will be made of S690 circular hollow sections and K-joints cast members made of G10MnMoV6-3 cast steel. The second truss will be made of S890 circular hollow sections and K-joints cast members made of G18NiMoCr 3-6 cast steel. Cast members in the truss behave as stiff joints, resulting in a combination of axial loading and secondary bending moments in the truss chords and braces. The test frame will consist of pull bars and large H-girders to withstand the dynamic loads. Special supports will transmit the force from the specimen and pull bars into large steel girders, see Figure 1. Currently the test frame is being designed and the trusses are in production. In the near future results on the large scale tests will be presented. The current paper shows the results of the small scale tests.

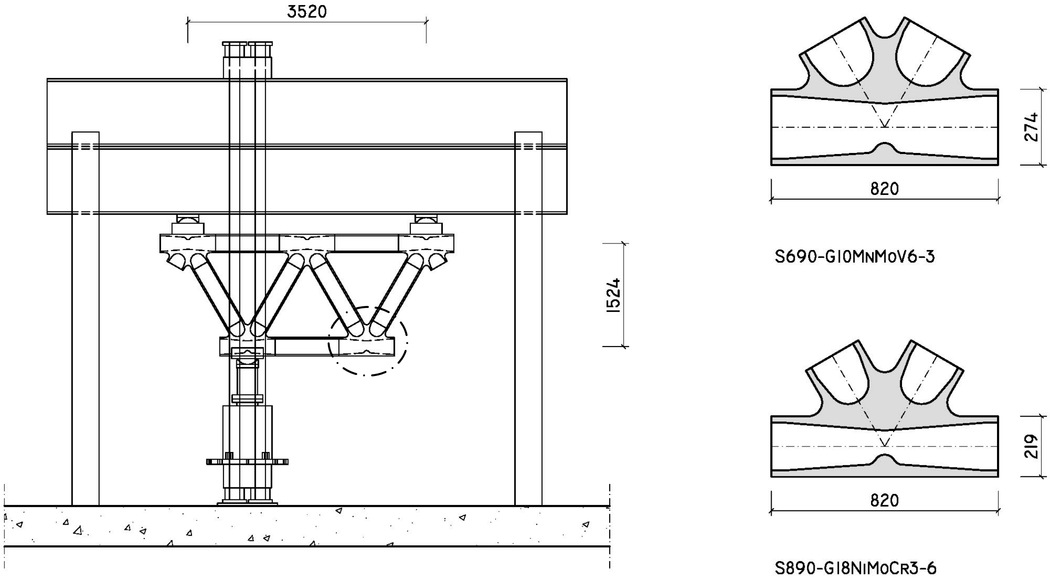

Figure 1. Conceptual drawing of large scale test setup for truss made of VHSS cast steel members and CHS.

2.2 *Small scale tests; V-welded hybrid plates*

In order to study the fatigue strength small scale experiments have been executed on V-welded hybrid plates. Based on a discussion with the industry it is chosen to test two weld variants, with ceramic backing (series CB) and without backing (series C) with equal plate thickness, see Figure 2. Table 1 shows the small scale test program and the mechanical properties of the rolled and cast steels. Table 2 shows the weld parameters that were used in the production of the specimens. The cast plates satisfy the NDT requirements of class 1 for weld areas and class 2 for other areas, by ultrasonic inspection according to EN 12680-1 (2003) and penetrant inspection according to EN 1371-1 (1997). All welds satisfy the weld quality B/C according to EN-ISO 5817 (2003), regarding the excess of weld metal in the weld toe and weld root region and the weld toe angle; for the weld root angle no prescription is given in that code.

Table 1. Mechanical properties

Series	Rolled grade	Cast grade	#	Rolled grade	R_{eh}	R_m	El. %	-40°C [J]
C46x	S460G2+M	G20Mn5	9	S460G2+M	469	590	31	222
C69x	S690	G10MnMoV6-3	9	S690	792	843	17.9	101
C89x	S890	G18NiMoCr3-6	9	S890	993	1058	15	36
CB46x	S460G2+M	G20Mn5	5	G20Mn5	502	611	26	99
CB69x	S690	G10MnMoV6-3	3	G10MnMoV6-3	745	808	19	41
CB89x	S890	G18NiMoCr3-6	6	G18NiMoCr3-6	983	1055	14	42

Initially the cast steel members have been cast in thickness 35 mm. After casting, the plates were quenched and tempered, and machined down to 25 mm thickness. The rolled material plates were plasma cut and welded to the cast plates, after which individual strips were plasma cut from the welded plates. For the welding a V-shape, with a bevel angle of 60° and a gap of 3 mm was chosen. Finally, the strips were ground to a width of 150 mm, see Figure 2.

Table 2. Weld parameters

Series	Backing	Weld process	Consumable	Preheat T (°C)	ISO 5817 (2003) Excess weld metal Toe	Root	Weld toe angle
C46x	-	FCAW	E80CG (rt)/E81T1K2M	-	B	B	B
C69x	-	GMAW/FCAW	ER100SG (rt)/E111T1K3	100	B	C	C
C89x	-	FCAW	E120T1G	125	B	C	B
CB46x	Ceramic	FCAW	E81T1K2M	-	B	B	B
CB69x	Ceramic	FCAW	E111T1K3	100	B	B	B
CB89x	Ceramic	FCAW	E120T1G	125	C	B	C

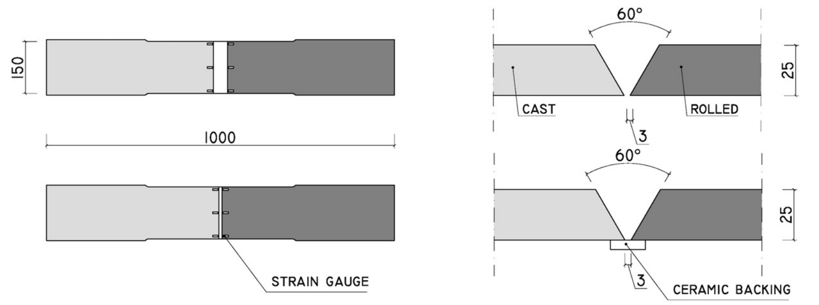

Figure 2. Geometry of small scale test specimens.

In the vicinity of the welds strain gauges were attached, monitoring the strain distribution along the weld toe and weld root. An alarm setting was used to switch off the test rig when differences in strain ranges were monitored, indicating a crack growth next to the strain gauges. From that moment crack growth in length and in plate thickness direction were monitored visually. If the monitoring of crack growth in thickness direction was not possible the crack marking procedure was applied, resulting in beach marks at the crack boundaries, visible after fracture.

3 CRACK GROWTH

For a qualitative comparison of the fatigue experiments on the small scale specimens a fracture mechanics model was used simulating the crack growth in the V-welded plates.

3.1 *Crack growth model*

In welded structures fatigue cracks are expected to grow from initial flaws. With the fracture mechanics approach a simulation of the crack growth of these initial defects can be made. The key geometry parameter is the stress intensity range, ΔK, which is a function of the applied stress range, crack size and local geometry. According to the Paris law, Equation 1, the crack growth rate can be described as a function of the stress intensity range and the material parameters C and M. For 3-dimensional geometries crack growth in both the depth and width direction has to be considered simultaneously (Dijkstra 1997). BS7910 (2005) gives calculation rules for the stress intensity range, based on correction factors for the local geometry and correction factors for the weld shape. The correction factors are functions of the non-dimensional geometrical parameters like relative crack depth (a/T), crack aspect ratio (a/c), relative weld length (L/T), plate width W, and weld toe angle θ. Figure 3 illustrates the parameters next to quarter elliptical and semi elliptical crack shapes.

$$\frac{da}{dN} = C_a * \Delta K(\sigma, Y)^{M_a}; \frac{dc}{dN} = C_c * \Delta K(\sigma, Y)^{M_c} \quad (1)$$
$$Y = f(a, c, T, W, L, \theta)$$

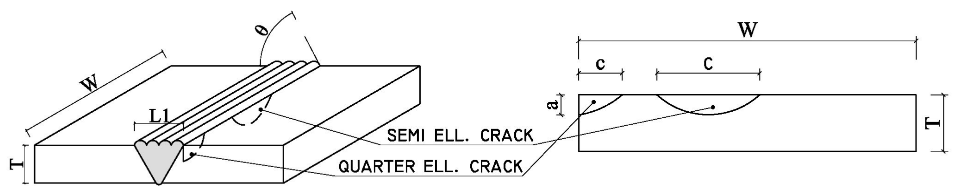

Figure 3. Geometrical parameters of V-welded hybrid connection.

MathCAD-routine FAFRAM, developed by TNO (Dijkstra 1997) makes it possible to make a numerical integration of crack growth in depth and width direction as a function of the stress intensity factor. Table 3 shows the parameters used in FAFRAM for the simulation of crack growth in the weld toe region.

Table 3. Model parameters; see also Figure 3.

Initial crack size	$a_i=c_i$	0.15	[mm]
Thickness plate	T	25	[mm]
Width plate	W	150	[mm]
Weld width cap size	L1	40	[mm]
Weld shape angle	θ	25	°
Crack growth exponent, Paris law	M	3	-
Crack growth constant, Paris law	C	$1.832*10^{-13}$	$Nmm^{-3/2}$
Loading mode	Bending, weld toe crack		

Figure 4 presents the crack growth data calculated with the FAFRAM model in relation to the measurements of the small scale fatigue experiments. Depending on the location of initiation the modelled crack shape was either quarter elliptical (edge crack) or semi elliptical (middle crack), which is of influence on the stress intensity range. Therefore, the crack shape is taken to account in the model. The crack growth of quarter elliptical cracks and semi elliptical cracks was calculated for three stress range levels, $\Delta\sigma$ = 180;230;280 MPa. The figure shows the crack length c, parallel to the weld vs. the number of cycles. Semi elliptical cracks are depicted as "se", the relatively faster growing quarter elliptical cracks as "qe". The failure criterion used in the model was either a crack length of ½*W or a crack depth of ½*T. The corresponding number of cycles to failure, N_f, is also presented in the S-N curve of Figure 5.

3.2 *Experiments*

In the experimental bending setup the specimens have been loaded in two modes, either resulting in tensile stresses at the weld toe, V-mode, or tensile stresses at the weld root, L- mode, see Figure 5. The specimens were loaded in approximately three nominal stress ranges, 180;230;280 MPa. The measured displacements and forces have been used to calculate the nominal stress ranges. As expected, most fatigue cracks initiated near the weld, from the edge or the middle of the specimens of both the rolled and the cast material. The results of specimens loaded in the V-mode can be compared to the FAFRAM simulation. Figures 4a and 4b give the measured crack growth parallel to the weld for various specimens. Although the scatter of the measurements is rather high, the model gives an adequate lower bound prediction for the crack growth. The model prediction seems to be more adequate for the high stress levels than for the low stress level of 180 MPa.

In general, loading mode L resulted in earlier crack growth. The reason for this could be the steeper weld angle of the weld root that may cause a higher local stress concentration in the HAZ. The specimens welded with ceramic backing were expected to have a smaller weld angle because of the use of backing. In practice it showed that the weld angles were even higher compared to the specimens welded without ceramic backing. Remarkably, in the specimens of the CB46x, CB89x and C89x series loaded in the L-mode cracks initiated from the cast material far away from the weld. A reason for this could be the quality difference of the cast material, defect group 1 near the weld and defect group 2 at the remaining locations, resulting in relatively larger initial defects. In a later phase of this research fracture surfaces will be inspected to find the crack initiation locations.

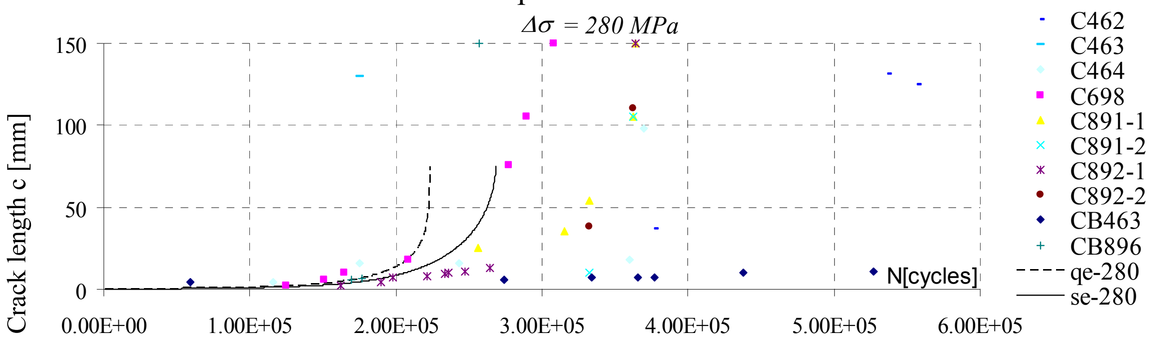

Figure 4a. Crack growth data.

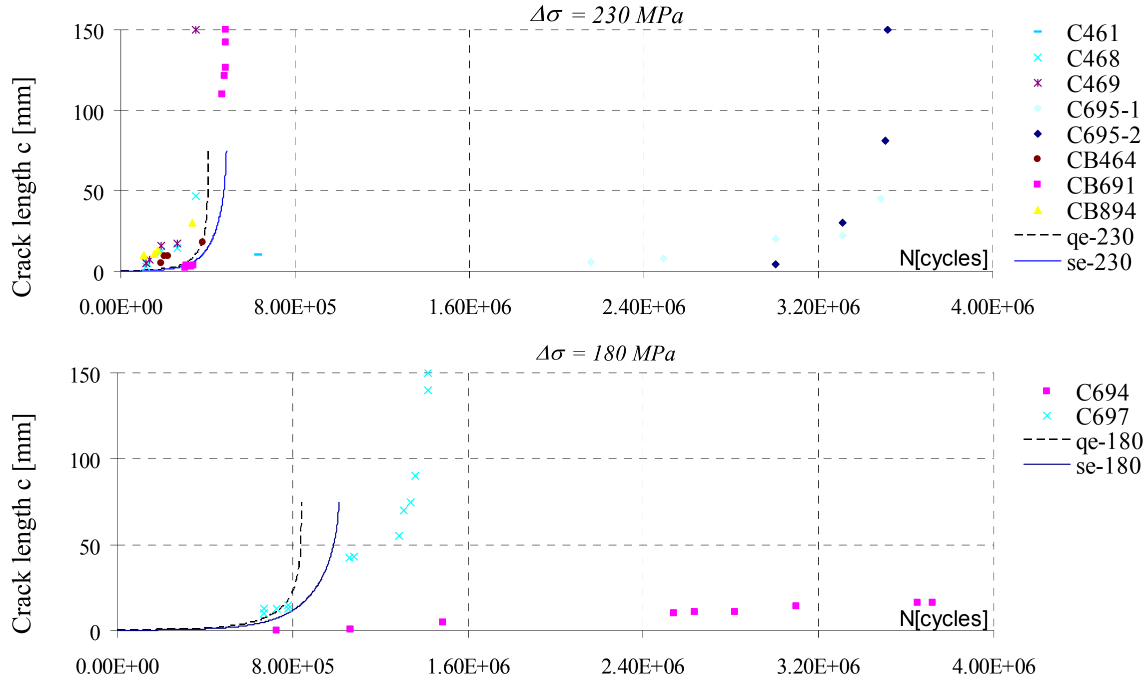

Figure 4b. Crack growth data.

4 FATIGUE STRENGTH

The results of fatigue tests of the small scale tests are presented in S-N curves, see Figure 5, giving the number of cycles until total fracture of the specimen vs. the applied nominal stress range. Some specimens have not yet been loaded until total fracture. Also these unbroken specimens, containing long cracks, are presented in the figure. The C89x series contains several specimens that did not have any crack initiation, indicated as run outs. Next to the results the design line of the EN 1993-1-9 (2005) for V-welded plates is given, detail class 71, with a characteristic stress range of 71 MPa at $2*10^6$ cycles and a slope m = 3. Also, for comparison, the results of the FAFRAM model are included in the S-N curve showing the number of cycles until failure for three stress ranges.
According to Hobbacher (2004) the characteristic stress range values at 2 million cycles, $\Delta\sigma_c$, have been calculated for a 95% survival probability on a two-sided confidence level of 75% of the mean, based on Equation 2. In the statistical evaluation only the specimens with crack initiation near the welds have been taken into account. As a save approximation the non-broken specimens have been included in the evaluation. For comparison with the Eurocode the results of 29 specimens are evaluated with a fixed slope value m = 3; the run outs have not been included in the evaluation. In an evaluation with a free slope the results of 33 specimens have been evaluated with a free slope, including the run outs. In table 5 the results of the statistical evaluation are listed.

$$\log N_c = (a - k * Stdv) - m * \log \Delta\sigma_c \qquad (2)$$

Table 5. Fatigue results

Evaluation	Fixed slope	Free slope
#specimens	29	33
k	2.15	2.15
$\Delta\sigma_{mean;2*10^6}$	154	174
$\Delta\sigma_c$	85	103
m	3	3.7

In some of the specimens cracks initiated from the base materials at a distance from the weld. This may be due to the presence of internal defects in the castings as the cracks all initiated at the cast steel side. Figure 6 shows the S-N curves of defect groups 1 and 2 according to UEG (1985) and the specimens with failure in the base material. The calculations of the fatigue strength in relation to the internal defects give a safe approximation. The S-N curve for plain rolled steel plates, $\Delta\sigma_c$ = 160 according to EN1993-1-9 (2005), gives an unsafe prediction regarding the fatigue strength of the non-welded parts of the cast members.

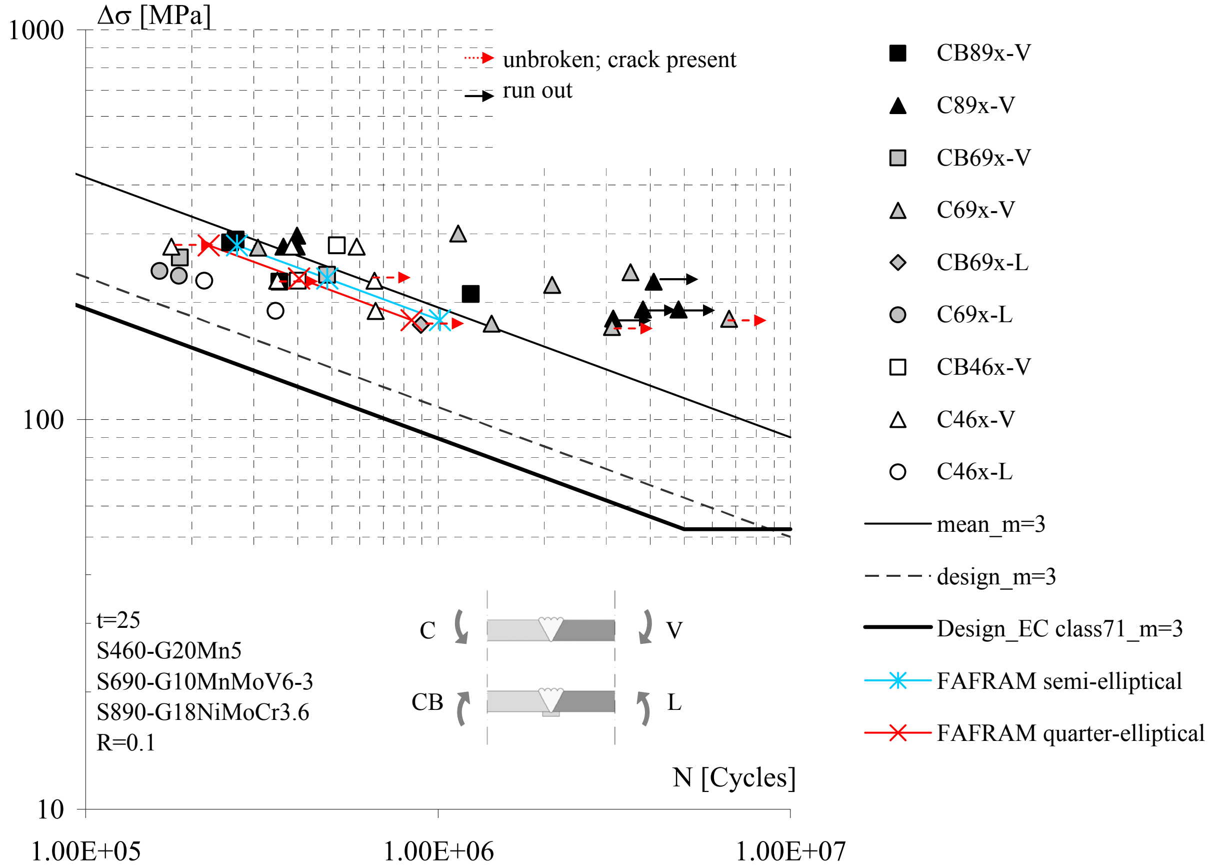

Figure 5. Fatigue strength curve of cracks initiating from the HAZ.

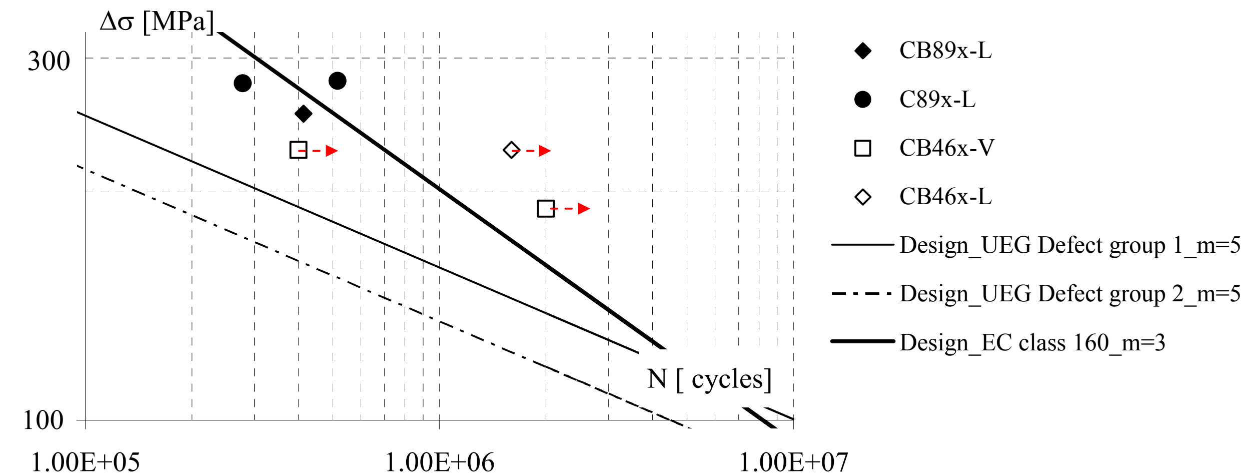

Figure 6. Fatigue strength curve of cracks initiating from base material.

5 CONCLUSIONS

The use of VHSS in welded connections requires high fabrication quality and avoidance of large stress concentrations in joints. Within the current study V-welded hybrid plates, made of rolled and cast steels with nominal yield strengths 460, 690 and 890 MPa were tested in order to determine the fatigue strength. The fatigue class 71 according to the Eurocode seems to be on the conservative side. Statistical evaluation of the test results shows that the characteristic fatigue strength at $2*10^6$ cycles, $\Delta\sigma_c$ = 85, with a slope m=3 and $\Delta\sigma_c$= 103, with a slope m=3.7. Most cracks initiated at the HAZ next to the weld locations. Qualitative fracture mechanics calculations verified the lower boundary of the fatigue results. The use of a ceramic backing is not found to give a higher fatigue strength. On the contrary, the steeper weld root angle of the specimens welded with use of ceramic backing resulted in a lower fatigue strength.

The number of specimens is too low to evaluate the influence of yield strength. However, the 690 and 890 MPa yield strength specimens seem to have a higher fatigue strength at lower stress levels compared to the 460 MPa yield strength specimens. At higher stress level this difference cannot be noticed. Some of the specimens had cracks in the base material. Calculation rules for the crack growth as a result of internal defects in cast members (UEG 1985) are on the safe side.

6 ACKNOWLEDGEMENTS

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7 SYMBOLS

ΔK	Stress intensity range
$\Delta\sigma_{mean}$	Mean stress range at $N=2*10^6$ cycles
$\Delta\sigma_c$	Characteristic stress range at $N=2*10^6$ cycles
a,c	Crack length in depth respectively length direction
C	Crack growth constant, Paris law
M	Crack growth exponent, Paris law
k	Number of standard deviations from the mean
m	Slope of fatigue strength curve
N_f	Number of stress cycles until failure
R	Stress ratio

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