Fatigue strength of repaired welded connections made of very high strength steels

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Fatigue strength of repaired welded connections made of very high strength steels

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Abstract

Modern steel manufacturing techniques make it possible to produce steel with the nominal yield strength up to 1300 MPa for structural purposes. However, the application of very high strength steels is still limited in the civil engineering structures due to lack of knowledge about the effects of the manufacturing process and experimental results regarding the structural behaviour of the material. Moreover, in a fatigue loaded very high strength steel structure absolute and relative stress variations will be higher compared to stresses in structures made of lower steel grades. Accordingly, the fatigue issue will be one of the most important design criteria for very high strength steel structures. In this current study, V-shape welded specimens were manufactured from S690 and S890 rolled steels and cast steels with similar yield strengths. Fatigue cracks were created in the weld toe of the specimen under a fluctuated loading and subsequently the fatigue damaged specimens were repaired by the removal of the cracks with subsequent welding. The fatigue strength curves of repaired specimens are compared with the detail categories of EN 1993-1-9 (2006) and the fatigue strength curves of the test results in the as-welded condition from literature. The fatigue strength of the fatigue damaged connections was completely recovered by the established repair procedure.

Keyword: Very high strength steels, cast steels, repair weld, hybrid connections, HiFIT

1. Introduction

The technological developments make it possible to produce very high strength steels for various applications. Especially, the application of very high strength steels in the automotive industry has enormously increased in the last decades. Although very high strength steels with good weldability, toughness and yield strength up to 1300 MPa are available for structural application purposes, the use of very high strength steels in civil engineering structures is rather limited due to limited knowledge about the consequences of the manufacturing process and the limited availability of experimental evidences of the structural behaviour of the material. In case of welded connections, the welding material is available with the yield strength up to 960 MPa. This leads to fabricate the welded connections in undermatch conditions which also need to be taken into account during design stage of the connections.

The use of very high strength steels leads to slender members with reduced wall thicknesses. Consequently, the reduction results in low self-weight and volume of structures which provide cost saving in production, transportation and erection. Additionally, the slender members with thin wall thicknesses will allow for the smaller weld volumes and as a result, decrease in weld consumables and lower energy consumption to make the welded connections. However, high strength steel structures will be exposed to high stress variation under fluctuated live load due to its low self-weight. Consequently, the fatigue strength of very high strength steel structures is one of the main design aspects of the effective applications.

Gurney (1979), concluded that the fatigue strength of the material becomes more susceptible to the presence of notches and to the surface condition with the increase of the material yield strength. Accordingly, with lower stress concentrations, the fatigue strength sensitivity can be decreased. With disregarding this issue, the fatigue strength of the material increases with the higher yield strength of the material. In the case of welded connections, it is a well-known event from Maddox (1990) that the fatigue strength is independent of the yield strength of the base material. It is assumed that the welding application results in micro-cracks which are likely to give rise to fatigue cracks. In other words, the fatigue life of welded connections is occupied by the fatigue crack propagation life which depends on stress range, being independent of yield strength. Research has been carried out on the fatigue performance of the base material and welded connections made of very high strength steels during the last decades. Demofonti et al. (2001) carried out axial fatigue tests on the butt welded plate specimens with 10 mm thickness made of S355 up to S960. The test results showed that no significant fatigue strength differences exist under constant amplitude loading in terms of use of very high strength steels.

Nevertheless, the beneficial effects for the S960 steel were found under variable loading condition. In addition, it was found that reduction of the notch factor, which was achieved by machining welds, gives an advantage for very high strength steels. Puthli et al. (2006), performed fatigue tests on various butt welded plate specimens with a thickness of 6-8 mm made of S690, S960 and S1100 in the framework of a research program of ECSC. The characteristic fatigue strength of all steel grades was found to be above the recommended values of EN 1993-1-9 (2006). The results of the specimens made of S1100 showed that the free slope decreases to m = -5 which is lower than the value of m = -3 in the design codes utilised. As a consequence of the slope decrease, the characteristic fatigue strength at $2 \cdot 10^6$ cycles increases at the high cycle region. Kuhlmann et al. (2006) showed that the post weld impact treatment techniques are very effective for increasing the fatigue strength of welded connections made of very high strength steels. The effectiveness of post weld impact treatments on fatigue strength of very high strength steels is already standardised in IIW recommendations [Marquis, et al. 2016]. Pijpers, (2011) investigated the fatigue strength of the base material of high strength steels and the welded connections made of very high strength steels. The main focus was put on the specimens made of S690, S890 and S1100. The main conclusion was that the fatigue crack initiation life of very high strength steels is longer than mild strength steels. The results of this study will be taken as a reference for the test results within the current study.

The main conclusion from fatigue tests on welded connections made of very high strength steels is that reduction of stress concentration/notch factor and application of a post weld impact treatments lead to beneficial advantages of very high strength steels in terms of fatigue strength. This result triggers researchers to find solutions for welded connections with lower stress concentrations. In this context, the welded connections with cast nodes can be one of the solutions. The ability of choosing optimal shape of the cast steel parts could result in connections with low stress concentration at intersection locations of the members and also the welds will be shifted out of the most intense stress locations. Accordingly, the fatigue strength of the hybrid welded connection between the cast steel joint and the rolled steel members becomes an important investigation. Mang et al. (1999) performed fatigue tests on welded cast steel plates with a thickness of 25-40 mm under constant amplitude loading with R = 0.1. The welding of the specimens was executed with and without a backing plate. The steel type used was St52-3 (S355 according to EN 10025-2) and cast steel type GS-20Mn5. Statistical analysis on the test data resulted in the characteristic value at $2 \cdot 10^6$ cycles, $\Delta\sigma_c$ = 87 MPa for the specimens with backing plate and $\Delta\sigma_c$ = 123.5 MPa for the specimens without backing. Puthli et al. (2007) executed fatigue tests on welded connections between circular hollow sections and cast nodes under bending and tension loading conditions. The test specimens were manufactured in different variations such as with same inner diameter, same outer diameter, with and without a backing plate and misalignment tolerances. The steel type used was S355 and S460 and the corresponding cast steel grades G20Mn5+QT and G10MnMoV6-3+QT3. The tests results showed no considerable difference between fatigue strength of S355 and S460 specimens. In all specimens, the fatigue cracks initiated at the root of the weld. Pijpers et al. (2009) carried out fatigue tests on V-shape welded hybrid plate specimens made of S460, S690 and S890 rolled steel plates to cast steel plates with similar yield strength. It was found that the specimens made of S690 and S890 have a higher fatigue strength compared to the specimens made of S460.

The state of art shows that with the modification of the conventional design methodology, the use of very high strength steels can give an advantage regarding fatigue strength of the base material as well as for the welded connections. On the other hand, fatigue crack initiation is inevitable in welded steel structures exposed to a fluctuated loading. Therefore, maintenance and in some cases fatigue life extension are essential for the welded steel structures. During the maintenance and for the fatigue life extension, the detected fatigue cracks need to be repaired. However, there is limited knowledge available about fatigue crack repair procedures and a possible fatigue life extension after the repair of very high strength steel structures. In order to investigate the fatigue strength of repaired welded connections made of very high strength steels, TU Delft initiated a research program in 2013. The current paper presents the fatigue strength of the repaired V-shape welded connections made of very high strength steels.

2. Literature review on repair of fatigue cracks

For the repair of fatigue cracks and retrofit of fatigue damaged connections or members, various methods have been developed. These methods can be grouped based on the applicable crack depth into two categories; the repair methods for shallow fatigue cracks and repair methods for deep fatigue cracks. The shallow fatigue cracks can be repaired by grinding, peening and Gas Tungsten Arc (GTA) remelting. Table 1 presents the summary of the repair methods for shallow fatigue cracks. The grinding process is also used as a fatigue strength improvement method for welded connections by removing discontinuities at the weld toe and reshaping the weld to create a smooth transition between the weld material and the base material for the stress concentration reduction. According to Dexter, et al. (2013), the grinding method can be applied for the repair of fatigue cracks with a depth up to 2 mm. In addition, the execution of the grinding procedure for the fatigue strength improvement of welded connections is described by Haagensen et al. (2001) in the IIW recommendations. Peening is a cold working process which creates a plastic deformation at the surface of the material by impacting a tool or metal balls and it is mainly used as a fatigue strength improvement method. The application process and quality control procedure are extensively given in the IIW recommendations [Haagensen et al., 2001]. Peening is an effective method for repair of surface cracks with a depth up to 3 mm [Dexter et al., 2013]. The GTA process remelts a small amount of the weld toe and the base material by using a gas-shielded tungsten electrode to liquefy material and to re-establish the connection after the solidification. This method is effective for the repair of the surface cracks with a depth up to 5 mm. In addition, the GTA remelting process is also used as a fatigue strength improvement method by reshaping the weld toe to create smooth transitions between the base material and the weld material. The effectiveness of the method depends on the penetration of the remelting zone. Fisher, et al, (1994) concluded that the application with the argon helium shielding gas and a cone angle applied with 60˚ respect the material surface results in the most effective penetration of the remelting zone.

Table 1. Summary of the repair methods for shallow fatigue cracks.

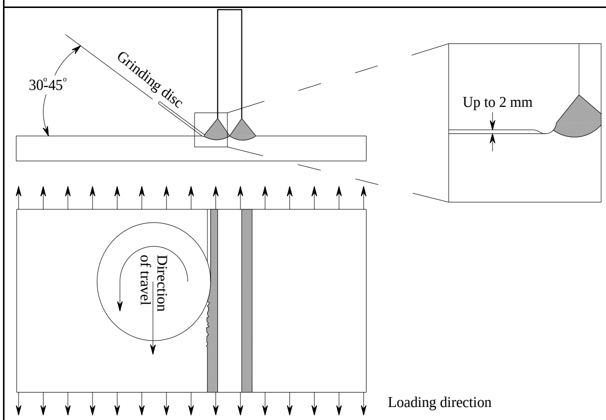
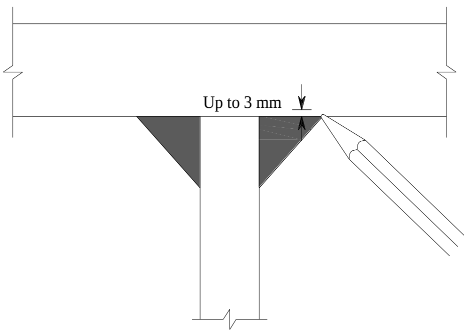
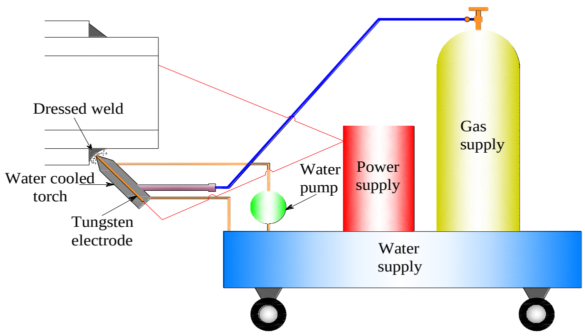
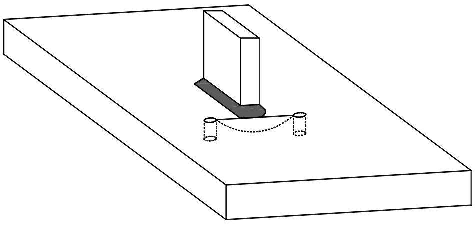
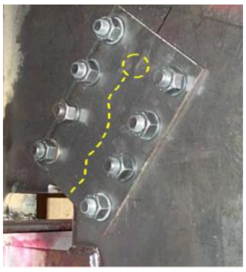
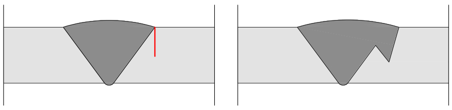
Schematisation	Repair method for shallow fatigue cracks
	**Grinding:** Applicable for the fatigue cracks with the depth up to 2 mm. 1. Advantageous ▪ improve weld toe, reducing stress concentration ▪ cost effective 2. Disadvantageous ▪ not possible to apply for complex joints ▪ risk to mask the crack tip
	**Peening:** Applicable for the fatigue cracks with the depth up to 3 mm. 1. Advantageous ▪ improve weld toe, reducing stress concentration ▪ introduce compressive stresses 2. Disadvantageous ▪ required highly skilled professionals ▪ difficult to apply to complex joints
	**Gas Tungsten Arc melting:** Applicable for the fatigue cracks with the depth up to 5 mm. 1. Advantageous ▪ improve weld toe, reducing stress concentration ▪ no additional filler material required 2. Disadvantageous ▪ required highly skilled welders ▪ difficult to apply to complex joints

Table 2. Summary of the repair methods for deep fatigue cracks.

Schematisation	Repair methods for deep fatigue cracks
	**Hole Drilling:** Applicable for the fatigue cracks with the depth above 5 mm. 1. Advantageous ▪ easy to apply ▪ appropriate solution for cracks in the base material 2. Disadvantageous ▪ cause inconvenience for users ▪ required good accessibility to crack position
	**Splice plate:** Applicable for the fatigue cracks with the depth above 5 mm. 1. Advantageous ▪ avoiding welding and deleterious effect of it ▪ lower stress range at the cracked sections 2. Disadvantageous ▪ required good accessibility to crack position from both side of connections ▪ required place for bolds installation
	**Re-welding:** Applicable for the fatigue cracks with the depth above 5 mm. 1. Advantageous ▪ well known process ▪ longer fatigue life with subsequent ultrasonic peening 2. Disadvantageous ▪ additional residual stresses ▪ deleterious effects of re-welding on the mechanical properties of the material.

The hole drilling method, the slice plate method and re-welding are commonly used processes for the repair of the deep fatigue cracks. The summary of these methods is given in Table 2. The application principle of the hole drilling method is to drill a hole at the crack tip to remove the sharp notch at the crack tip to inhibit further crack propagation. According to Dexter, et al. (2003), as a rule of thumb, holes with larger diameters show better performance in terms of fatigue strength retrofit. Based on field experience, Dexter, et al. (2013) recommends typical hole diameters in the range of 50 to 102 mm for steel bridge applications. However, the reduction in stiffness, the strength of the structures and the uncomfortable effects on the user of structures need to be taken into account for drilling larger holes. Haagensen (1994) recommended a formula for practical estimation of hole diameter and it was concluded that putting an entire fully tensioned high strength bolt into the hole improves the fatigue strength of the repaired section. This method is more suitable for fatigue cracks in the base material. With the splice plate method, the crack contained sections are covered with additional plates from both sides. The main principle of the method is to increase the cross sectional area at the concentrated sections to reduce stress range at the crack locations and consequently to prevent crack propagation. For the attachment of the additional plates, high strength bolts are preferable rather than welding from a fatigue strength point view. Yamasaki et al. (1984) concluded that the combination of the hole drilling method with the splice plate method can lead to a higher fatigue life extension than the fatigue life extension with only the splice plate method. The repair by welding is an effective method for the repair of long fatigue cracks in welded connections. The detected fatigue cracks are removed along the crack length up to the crack depth by preparing a suitable weld groove and filling the prepared groove by weld material. Borrego et al. (2009) concluded that the repair by welding is an effective method for fatigue cracks in welded connections. In case of fatigue cracks in the base material, the repair by welding is not preferable due to the deleterious effects of the welding process on the material properties and the residual tensile stress occurrence after welding application. Yamasaki et al. (1984) focused on the effects of the repair weld on the fatigue crack propagation behaviour in the base material and concluded that the fatigue crack growth rate in the base material repaired by welding is higher than the fatigue crack growth rate in the base material. Carrato, (1999) monitored the effectiveness of the repair by welding in a field application. A fatigue damaged railway bridge was repaired by welding and the bridge was regularly inspected after the repair. No new fatigue cracks have been detected after subjecting 20 million axle loads. Kudryavtsev et al. (2011) performed a research on the repair of the fatigue cracks at the weld toe of non-load carrying longitudinal attachments with the repair by the re-welding method. The fatigue tests were carried out on specimens in the as-welded condition, in the repaired condition by re-welding and in the repaired condition by re-welding with subsequent ultrasonic peening at the weld toe. The results showed that the repair by welding can recover the fatigue strength of the fatigue damaged connections. The repair with subsequent ultrasonic peening resulted in a significant increase in the fatigue strength of the repaired connections. In some specimens, the fatigue crack repair has been carried out two or three times and the results showed that the multiple repairs hardly affected the fatigue strength of the connection. Kudryavtsev et al. (2008) carried out fatigue tests on various repair methods for the repair of fatigue cracks in the base material. A hole was drilled in the middle of the plate test specimens and these specimens were exposed to a fatigue load to create fatigue cracks at the edge of the hole. The fatigue cracks were repaired/retrofitted by overloading, drilling a hole at the crack tips, drilling a hole at the crack tips with the installation of high strength bolts, local explosive treatment, local heat treatment and welding with and without ultrasonic peening of the weld toes. In case of repair by welding, the initial hole in the middle of the specimens was also filled with weld material. The test results showed that the longest fatigue life has been obtained by repairing the crack by welding with subsequent ultrasonic peening. The result of repair by welding without ultrasonic peening was the second effective method.

3. Experimental program

Based on the literature evaluation, an experimental program has been set up in the current study consisting of V-shape welded plate test specimens. The V-shape welded specimens are manufactured in two configurations: welded connections between rolled-rolled steels and welded connections between rolled-cast steels. The emphasise was put on the rolled steel grades S690 and S890 with the corresponding cast steel grades G10MnMoV6-3 and G18NiMoCr3-6.

3.1. Material properties

Table 3 gives the chemical composition and Table 4 the mechanical properties of the test materials. The values of the mechanical properties and the chemical composition are taken from the material certificates.

Table 3. The chemical composition of the test materials [%wt].

Materials	C%	Si%	Mn%	P%	S%	N%	Al%	Cu%
S690	0.17	0.24	1.19	0.011	0.002	0.004	0.094	0.02
S890	0.18	0.29	1.00	0.014	0.001	0.005	0.038	0.03
G10MnMoV6-3	0.11	0.44	1.65	0.011	0.002	-	-	-
G18NiMoCr3-6	0.2	0.45	1.07	0.012	0.002	-	0.025	0.11
	Cr%	Ni%	Nb%	Mo%	V%	Ti%	B%	Zr%
S690	0.31	0.03	0.03	0.2	0.003	0.002	0.0026	0.001
S890	0.58	0.96	0.02	0.33	0.05	0.004	0.0005	0.001
G10MnMoV6-3	-	0.35	-	0.26	-	-	-	-
G18NiMoCr3-6	0.9	0.8	-	0.57	0.003	-	-	-

Table 4. Mechanical properties of the test materials.

Materials	$R_{p,0.2}$	R_m	A5	KVC -40 ˚C [J]				KVC -60 ˚C [J]				HB
	[MPa]	[MPa]	%	1	2	2	AVG	1	2	3	AVG	
S690	749	802	18	-	-	-	-	155	145	181	160	-
S890	982	1069	12	46	53	47	49	-	-	-	-	-
G10MnMoV6-3	697	802	19.6	-	-	-	-	-	-	-	-	252
G18NiMoCr3-6	1006	1101	13.4	-	-	-	-	-	-	-	-	316

3.2. Fabrication and instrumentation

The G10MnMoV6-3 and G18NiMoCr3-6 steel plates were cast with a thickness of 40 mm. The plates were quenched and tempered after casting and the thickness was reduced to 25 mm by machining from both sides of the plates. The cast plates satisfy the NDT requirements of SM1/LM1/AM1 for magnetic particle inspection according to EN 1369 (1996) and class 1 for ultrasonic inspection according to EN 12680-1 (2000).

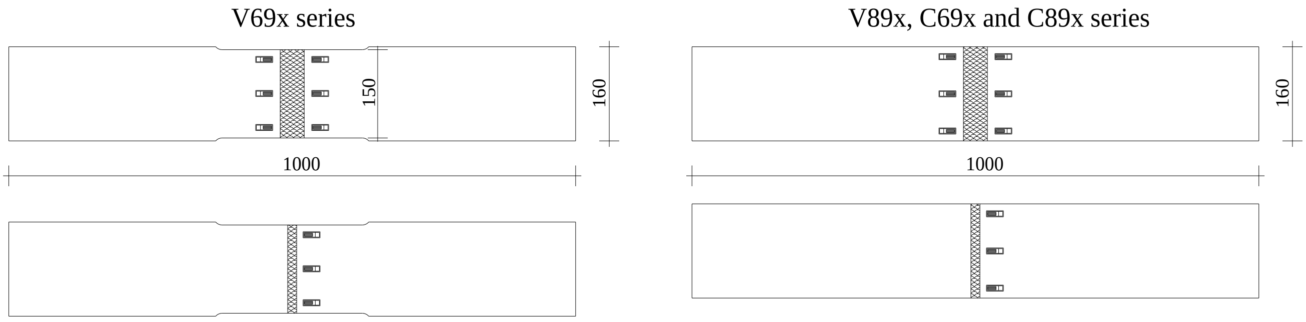


Figure 1. Geometry and dimensions of the test specimens.

The rolled steel plates were flame cut and the weld edges of the rolled plates and the cast plates were machined to prepare a bevel angle of 60˚. The prepared plates were welded by the FCAW process with a ceramic backing at the weld root. The individual test strips were plasma cut from the welded plates with a width of 160 mm and a length of 1000 mm (see Figure 1). Table 5 summarises the materials, weld parameters and geometry of the specimens for the test series of the current experimental program. Figure 2 illustrates the weld shape of the test specimens and a macro photo of the cross section of the weld, indicating the weld layers. Codes V69x and V89x are used for the specimens with rolled - rolled steel connections made of S690 and S890 respectively. Codes C69x and C89x denominate the hybrid specimens, cast – rolled steel connections, made of the steels with the nominal yield strength 690 MPa and 890 MPa respectively.

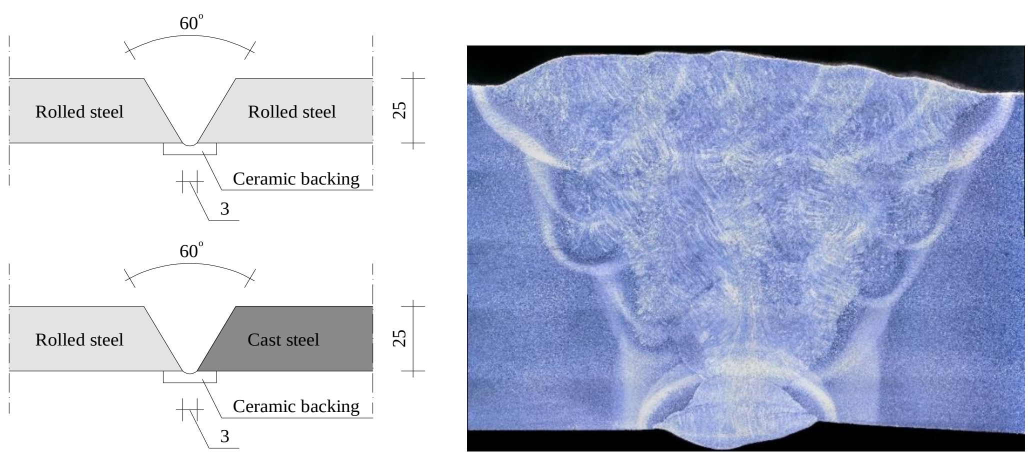


Figure 2. Weld configuration of the test specimens and a macro of the weld.

Table 5. The welding parameters of the test series.

Test series	V69x	C69x	V89x	C89x
Rolled steel grade	S690	S690	S890	S890
Cast steel grade	-	G10MnMoV6-3	-	G18NiMoCr3-6
Number of test specimens	9	9	9	9
Thickness [mm]	25	25	25	25
Length [mm]	1000	1000	1000	1000
Width [mm]	150	160	160	160
Preheat temperature ˚C (min.)	100	100	125	125-165
Interpass temperature ˚C (max.)	200	200	200	200
Consumable at cap	Megafill 742M	Megafill 742M	Megafill 1100M	Megafill 1100M
Heat input cap	0.8-1.4	0.8-1.4	0.8-1.4	0.8-1.4
Heat input fill	0.8-1.6	0.8-1.6	0.8-1.6	0.8-1.6
Consumable at root	Megafill 821RM	Megafill 821RM	Megafill 821RM	Megafill 821RM
Weld process	FCAW	FCAW	FCAW	FCAW
Heat input root	1.2-1.8	1.2-1.8	1.2-1.8	1.2-1.8
Backing	Ceramic	Ceramic	Ceramic	Ceramic
Gap [mm]	3	3	3	3

Strain gauges are attached to the specimens to measure the strain distribution at the surrounding of the weld and to determine the fatigue crack initiation life of the specimens. By using these strain gauges, an alarm system has been set up to shut off the test rigs in case of 50 µstrain deviations of strain range measurements. Accordingly, the region of the strain gauge is visually inspected to discover the location of possible fatigue cracks. The strain gauges were applied 10 mm from the weld toe of the weld cap and the weld root. Three strain gauges were attached to each side of the weld toe of the cap and 3 strain gauges at one side of the weld toe of the weld root (see Figure 3).

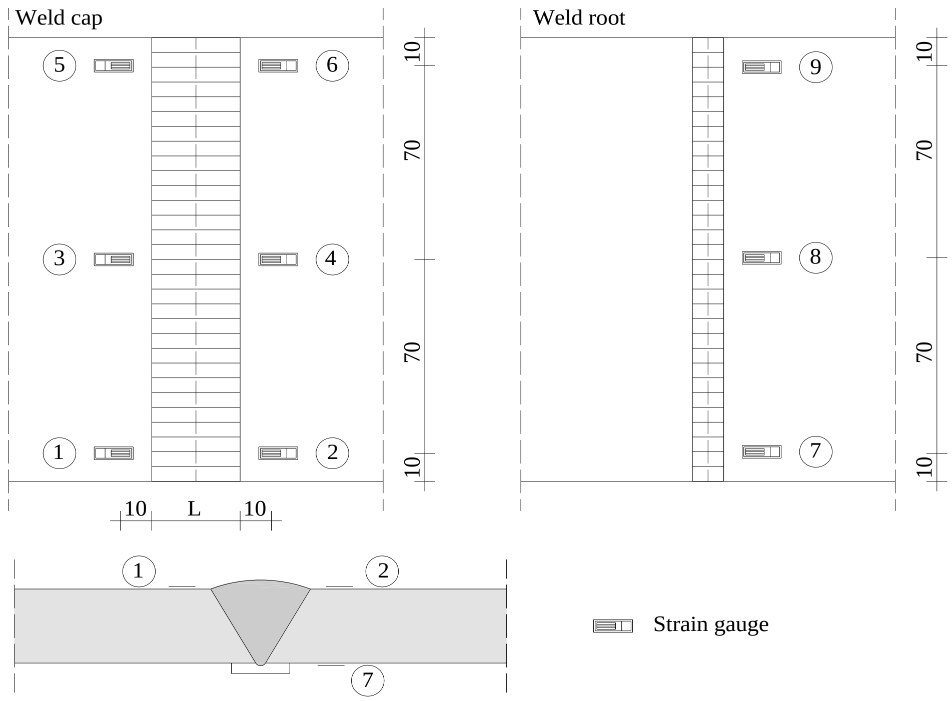


Figure 3. Strain gauge configuration on a test specimen.

3.3. Test rigs

In the Stevin II laboratory of the Delft University of Technology, two four point bending test frames have been set up for the fatigue tests on the V-shape welded plate specimens. Figure 4 shows the fatigue test rigs where on the left side, a single plate setup is illustrated and on the right side, a twin plate setup is presented. By using these test setups simultaneously, a large number of tests can be performed in a relative short time. As the plates are loaded in the four point bending test frames, a continuous bending moment is present on the weld area, resulting in a compressive and a tension zone. The specimens are loaded such as the weld cap exposes to the tensile stresses. The fatigue test specimens are tested with stress ration R = 0.1 and with the loading frequency of 3 Hz.

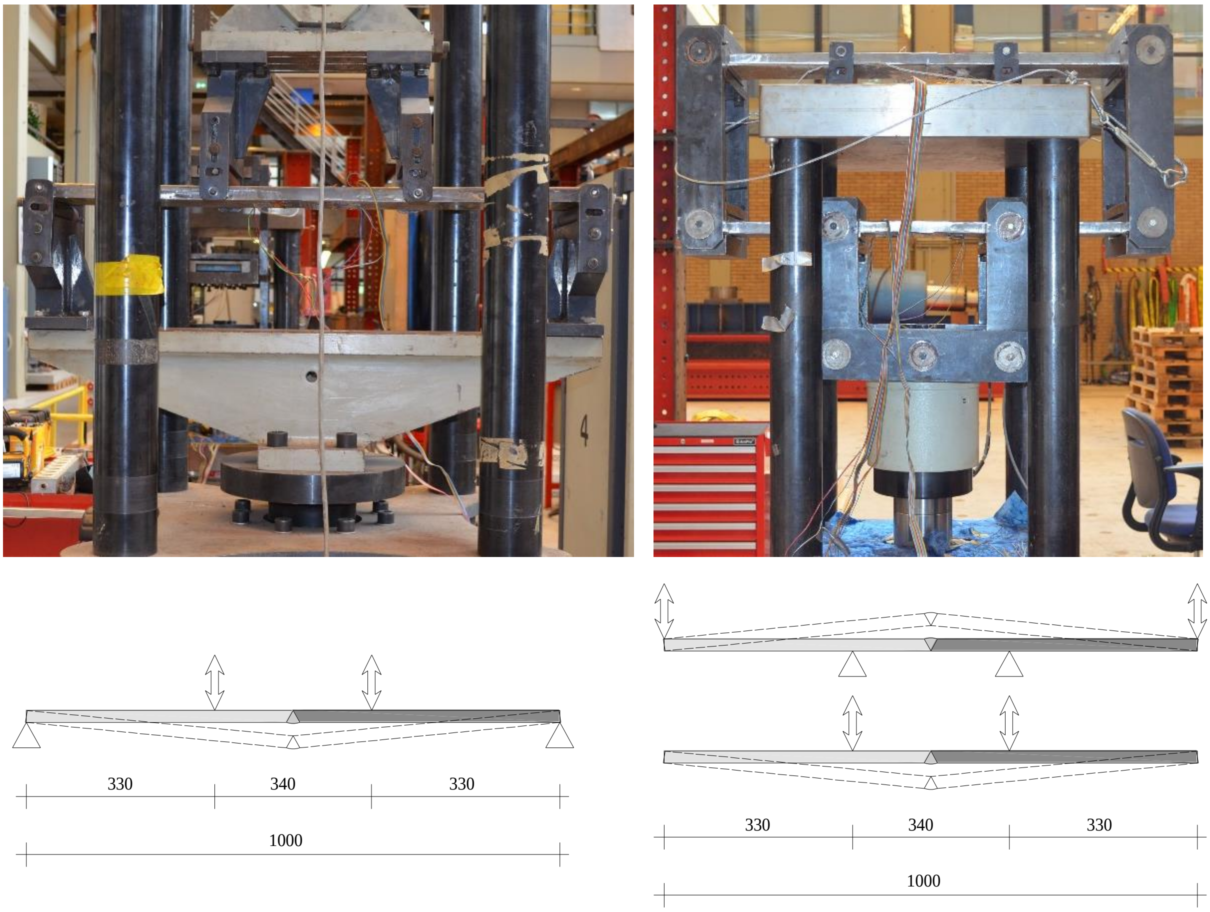


Figure 4. Four point bending test rigs for fatigue tests and the loading condition of the test specimens.

4. Repair of the fatigue cracks

First, a fatigue test was carried out on the V-shape welded plate specimen to create fatigue cracks. After initiation of the cracks, the growth of the cracks was monitored visually. The fatigue crack growth was permitted until the length of the crack reached to half the width of the test specimen and this first testing stage is called the fatigue crack creation stage. Fatigue test results of this stage are not evaluated in this paper. After the fatigue crack creation stage, the fatigue damaged welded connections were repaired by removal of the cracks with subsequent filling of the groove by welding.

The performed visual inspection during the fatigue crack creation stage may lead to inaccurate crack length detection which depends on the visibility of cracks, accessibility to the crack locations and the person who performs the inspection. For the detection of an accurate crack length and all possible other small cracks, the application of a NDT method is essential. Accordingly, all fatigue damaged V-shape welded specimens were examined by a magnetic particle inspection and the detected cracks were marked to specify the crack boundary for the crack removal process (see Figure 5).

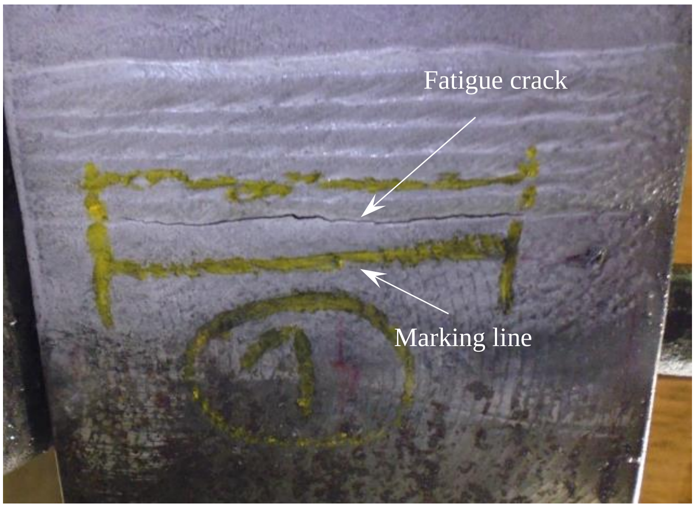


Figure 5. Detected fatigue crack in a specimen and marking line.

The fatigue crack removal process was executed with a disk and a burr grinder. The crack removal process was performed gradually and magnetic particle inspection took place regularly to avoid unessential material removal and a too deep weld groove. In the case of shallow cracks, the crack removal process was continued up to at least 1/3 of the material thickness to create an appropriate weld groove for a suitable weld quality. After the complete crack removal, the prepared weld groove was filled with the weld material by using the welding procedure of the original weld. For the repair of a weld toe fatigue crack at the edge of the plate, a temporary plate was attached to the specimen for providing a continuous welding and the temporary plate was removed after welding (see Figure 6).

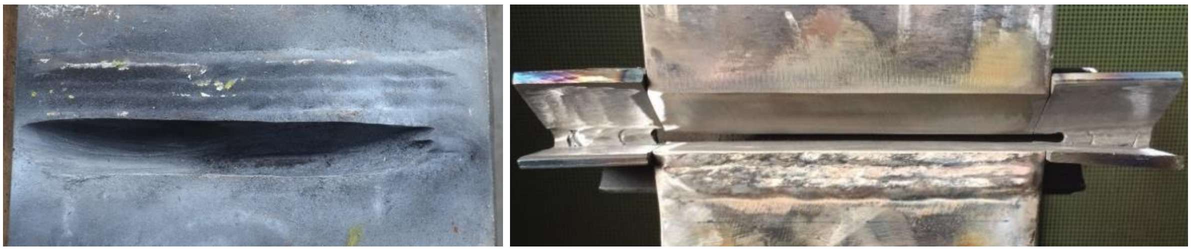
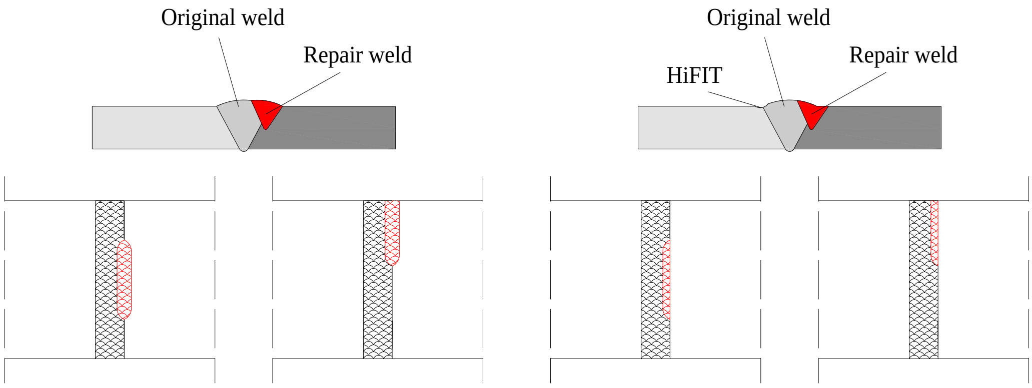


Figure 6. A weld groove after crack removal process and attached temporary plate at the edge of a specimen.

In general, V-shape welds are utilised for connections that are not possible to perform welding from both sides. It also means that the weld root is inaccessible for the fatigue crack inspections and these cracks may be visible when the cracks reach the weld cap. Consequently, the repair of these cracks can also be performed from the weld cap. During the fatigue crack creation stage, fatigue cracks were observed at the weld toe of the weld root, although the root of the weld was subjected to the compression stresses due to the loading. The fatigue cracks in the weld root have been repaired from the weld cap side by removing the material from the weld cap through the thickness of the weld.

Figure 7. Removal of the crack at the weld toe of the weld root.

In practice, repair of fatigue cracks in structures is carried out at service conditions where the repaired connections are constrained by the surrounding structural elements. For the simulation of realistic repair conditions, the specimens were constrained during the application of the repair weld. The repair welds were examined by a magnetic particle and ultrasonic inspection for the weld qualification. After the repair of the weld toe cracks, the repair welds cause geometrical changes of the welded connection and it consequences a disruption of the stress distribution around the welded connection (see Figure 8a). Especially, the intersection between boundaries of the repair weld and the original weld cause a sharp geometrical change and consequently a high stress concentration. For the elimination of these undesired effects of the stress concentration, the repaired welded connections were reshaped by grinding to smooth transition between the original and repair weld (see Figure 8b). The grinding process is limited with the removal of the start-stop points of the repair weld and additional weld material at the weld toe (see Figure 8c). Furthermore, after the fatigue crack repair, the repaired side of the connection has a new weld toe and the other side of the weld contains the weld toe of the original weld which still contained the cyclic load history from the fatigue crack creation stage. According to the cumulative damage rule of Miner, fatigue crack initiation in the original weld toe is highly possible after the repair. The main purpose of the research is to investigate the fatigue strength of the repaired welded connections made of very high strength steels. Therefore, the cracks initiation in the original weld toe needs to be prevented. For this purpose, the weld toe of the original weld was treated by the high frequency impact treatment (HiFIT) weld toe improvement method.



a) Weld geometry after the repair

b) Weld geometry after the grinding and treatment

c) Boundary of the reshaping by the grinding process

Figure 8. Weld shape after the repair and the repaired weld geometry after reshaping and HiFIT.

The repaired welded specimens were tested under the same conditions as the fatigue crack creation stage such as: four point bending test, same stress range and stress ratio R = 0.1. The specimens without crack initiation after testing for $5 \cdot 10^6$ cycles are indicated as run-outs.

5. Experimental results of repaired welded connections

At multiple locations, fatigue cracks initiated from the V-shape welded specimens such as weld toe of rolled steel, weld toe of cast steels, as well as in the base material of cast steels and rolled steel. All weld toe cracks initiated at the weld toe of the repair weld. In the V89x test series, the fatigue crack initiation was observed in the base material of three test specimens during the fatigue cracks creation stage and these specimens were not repaired. Accordingly, the test results of them were not presented in this paper. In the majority of the specimens containing S890 rolled steel, the fatigue cracks were observed in the base material of rolled steel. Table 6 presents the applied nominal stress range Δσ, the number of cycles at the crack initiation, N_i, the fatigue crack propagation life, N_p and the number of cycles at failure, N of specimens. The table also indicates the crack initiation locations and the ratio of the crack initiation life, N_i to the total fatigue life, N.

Table 6. Fatigue test results of repaired V-shape welded specimens made of very high strength steels.

Specimen	Crack initiation location	Test results				
		Δσ [MPa]	N_i [cycles]	N_p [cycles]	N [cycles]	N_i/N
V691	WT,cap,middle	203	1239493	499228	1738721	0.71
V692	run out	228	5022891	0	5022891	1.00
V693	WT,cap,middle	221	894634	804366	1699000	0.53
V694	WT,cap,middle	256	313418	250718	564136	0.56
V695	WT,cap,middle	253	30696	130289	160985	0.19
V696	run out	244	4575656	0	4575656	1.00
V697	WT,cap,middle	257	275968	203253	479221	0.58
V698	WT,cap,middle	285	269302	222234	491536	0.55
V699	WT,cap,middle	310	163269	167853	331122	0.49
C691	WT,cap,middle,cast	203	224510	1077650	1302160	0.17
C692	BM, middle, cast	254	370566	740631	1111197	0.33
C693	BM, edge, cast	255	71789	1260937	1332726	0.05
C694	WT,cap,middle,rolled	222	165382	260426	425808	0.39
C695	WT,cap,middle,cast	227	72839	314847	387686	0.19
C696	BM, middle, cast	265	104233	1269823	1374056	0.08
C697	WT,cap,middle,rolled	303	52813	185710	238523	0.22
C698	WT,cap,middle,cast	290	253770	119282	373052	0.68
C699	WT,cap,middle,cast	321	150430	197298	347728	0.43
V891	run out	250	5010863	0	5010863	1.00
V892	Base material failure at the crack creation stage, not repaired					
V893	run out	285	5000001	0	5000001	1.00
V894	Base material failure at the crack creation stage, not repaired					
V895	Base material failure at the crack creation stage, not repaired					
V896	BM, middle, rolled	292	101392	934346	1035738	0.10
V897	BM, middle, rolled	358	226237	334800	561037	0.40
V898	BM, edge, rolled	356	106595	454269	560864	0.19
V899	BM, middle, rolled	370	228910	203487	432397	0.53
C891	BM, middle, cast	260	218923	1414623	1633546	0.13
C892	BM, middle, cast	244	218923	841856	1060779	0.21
C893	BM, edge, rolled	265	703437	2067618	2771055	0.25
C894	BM, edge, rolled	298	627418	450370	1077788	0.58
C895	BM, middle, rolled	281	305269	912656	1217925	0.25
C896	WT,cap,middle,cast	302	69460	100911	170371	0.41
C897	BM, edge, rolled	349	52386	407571	459957	0.11
C898	BM, edge, rolled	343	237299	312324	549623	0.43
C899	BM, edge, rolled	372	50268	314663	364931	0.14

WT: At the weld toe
BM: Base material
Cap: Weld cap
Rolled, cast: Crack initiation at the weld toe of rolled or cast steel part
Middle, edge: Crack initiation at the edge of middle of the plate specimen

For evaluating effects of yield strength on the fatigue strength, it is necessary to analyse the test results based on the steel grade of the test specimens. However, it is not possible to perform a statistical analysis on the test results of the weld toe cracks of V89x series due to very limited available fatigue test data. The test results are statistically evaluated according to the fatigue crack initiation locations such as; weld toe crack at rolled steel side, weld toe cracks at cast steel side, base material cracks in the cast and rolled steels. The test results of the repaired V-shape welded specimens can be evaluated by comparing the results with a standard fatigue design curve. The design curves of Eurocode are set as reference curves for the comparison. The statistical analysis was performed according to Brozetti et al. (1989) which is also prescribed in EN 1993-1-9 (2006). The fatigue strength curves of the test results were determined by regression analysis of the test data using a free slope and a fixed slope with m = -3. The fatigue strength curves were estimated for the mean, lower bound and upper bound of the data scatter. The run-outs were excluded for the fatigue strength curves with the fixed slope and included for the fatigue strength curves with the free slope. The fatigue strength curves are presented by a log-log linear relationship between the nominal stress range, Δσ and the number of cycles up to complete fracture, N.

5.1. Weld toe cracks

Weld toe cracks in rolled steels

The statistical analysis was performed on the test data for the weld toe cracks in S690 and S890 rolled steels. In two specimens of the V69x series and two specimens of the V89x series, no fatigue cracks were observed and are indicated as run-outs. One run-out specimen of the V89x series was already a run-out during the fatigue crack creation stage and this specimen has been repaired by assuming that it contained a fatigue crack with the length of 75 mm in the middle of the weld toe at the weld cap. Fatigue cracks initiated in the other three specimens during the crack creation stage and these specimens became run-outs after the repair of the cracks. Table 7 shows the results of the statistical analysis on the test data of the weld toe cracks in the rolled steel parts.

Table 7. Results of statistical analysis on weld toe cracks in rolled steel parts.

	Slope	$\Delta\sigma_{mean}$	$\Delta\sigma_c$	Number of specimens
Weld toe cracks in rolled steel parts	-3.62	210	114	13
	-3.00	161	111	9

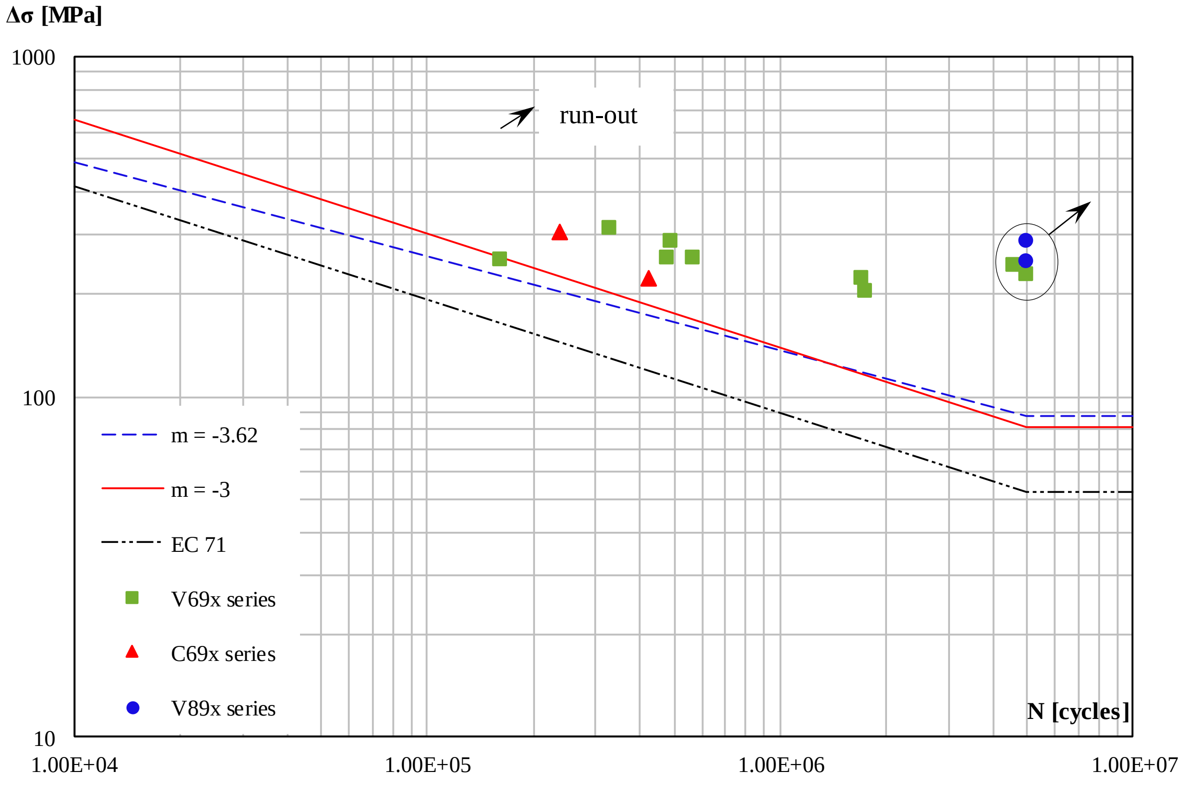


Figure 9. S-N curves of weld toe cracks in rolled steels of the repaired V-shape welded specimens.

Figure 9 presents the fatigue strength curves of the weld toe cracks in the rolled steel parts of the repaired V-shape welded specimens compared to the detail category 71 of EN 1993-1-9 (2006) which is recommended for the fatigue design of V-shape welded connections. The comparison shows that the recommended fatigue design curve of EN 1993-1-9 (2006) seems to be very conservative. Using a fixed slope of m = -3, the fatigue strength at $2 \cdot 10^6$ cycles is 111 MPa while the design value of EN 1993-1-9 (2006) is 71 MPa and analysing the test results for a free slope of m = -3.62 the fatigue strength at $2 \cdot 10^6$ cycles leads to 114 MPa.

Preferable a repaired connection should have at least the fatigue strength of the original connection; before the repair. Therefore, the effectiveness of the repair procedure can be evaluated by comparing the fatigue strength of the repaired connection with the fatigue strength of the original connection (before repair). Pijpers, (2011) carried out the fatigue tests on V-shape welded specimens made of rolled steels in the as-welded condition. The statistical analysis performed on those fatigue test results with weld toe cracks in S690 and S890 rolled steels and the results of the statistical analysis are given in Table 8.

Table 8. Results of statistical analysis on Pijpers (2011) data; as-welded condition.

	Slope	$\Delta\sigma_{mean}$	$\Delta\sigma_c$	Number of specimens
Weld toe cracks in rolled steel parts	-4.44	217	141	29
	-3.00	172	102	21

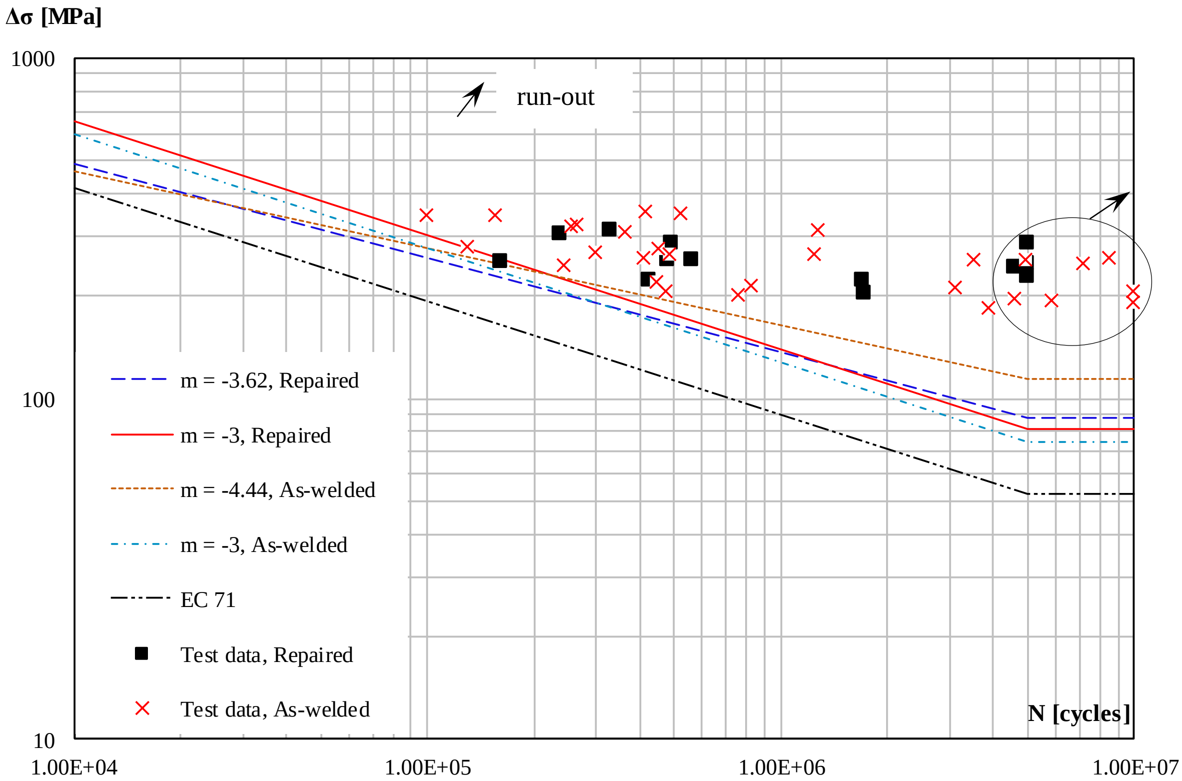


Figure 10. Comparison between S-N curves of weld toe crack in rolled steels of repaired and in the as-welded specimens.

Figure 10 compares the fatigue strength curves of repaired welded connections with the fatigue strength curves of welded connections in the as-welded condition. Due to a large number of run-outs in the test data of Pijpers (2011), a large deviation is determined between the fatigue strength curves with the free slopes. The fatigue strength at $2 \cdot 10^6$ cycles is 102 MPa for the fixed slope of m = -3 and 141 MPa for the free slope of m = -4.44. The fatigue strength curve with the slope of m = -3 of the repaired V-shape welded specimens ($\Delta\sigma_c$ = 111 MPa) reasonably matches with the fatigue strength curve of V-shape welded specimens in the as welded condition ($\Delta\sigma_c$ = 102 MPa).

Weld toe cracks in cast steels

In the hybrid welded connections, the fatigue cracks initiated at the weld toe of the cast steels and consequently the fatigue cracks repair process took place at the cast steels side. During re-testing of the repaired hybrid specimens, the fatigue cracks initiated at the weld toe of the repair weld at the cast steels side. The statistical analysis is performed on the test data of the weld toe cracks at the cast steel parts and the results of the analysis are shown in Table 9.

Table 9. Results of statistical analysis on weld toe cracks in cast steel parts.

	Slope	$\Delta\sigma_{mean}$	$\Delta\sigma_c$	Number of specimens
Weld toe cracks in cast steel parts	-2.91	153	100	5
	-3.00	156	112	5

Figure 11 presents the fatigue strength curves of weld toe cracks in G10MnMoV6-3 and G18NiMoCr3-6 cast steel of the repaired V-shape welded connections. The comparison is made with the detail category 71 of EN 1993-1-9 (2006) and it was found that the design curve leads to conservative fatigue strength. For the fixed slope of m = -3, the fatigue strength at $2\cdot10^6$ cycles is 112 MPa and the fatigue strength leads to 100 MPa at $2\cdot10^6$ cycles for analysing the test results with a free slope of m = -2.91.

EN 1993-1-9 (2006) does not distinguish between the fatigue design of cast steels and rolled steels. The fatigue design recommendations for welded connections made of cast steels are given in DNVGL-RP-C203 (2016). According to this design recommendation, the fatigue design category of rolled steels can be used for the cast steels as well. The recommended design class in DNVGL-RP-C203 (2016) for V-shape welded connections is the same as detail category 71 of EN 1993-1-9 (2006). Consequently, the fatigue strength curves of the repaired specimens satisfy the requirements of DNVGL-RP-C203 (2016).

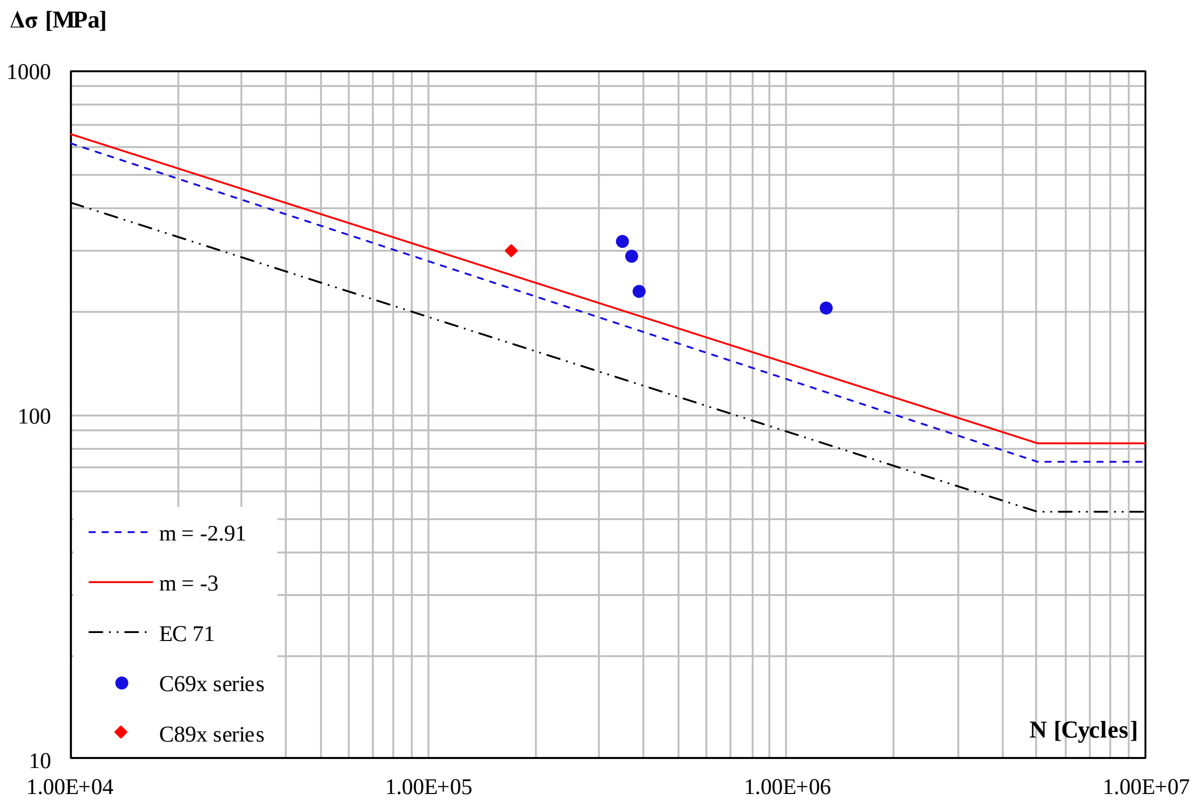


Figure 11. S-N curves of weld toe cracks in cast steels of the repaired V-shape welded specimens.

Pijpers (2011) also performed the fatigue tests on hybrid connections made of cast and rolled steels. The fatigue test results of the weld toe cracks in the cast steel parts are combined and the statistical analysis is performed on the test data. Table 10 presents the results of the statistical analysis on the test data of Pijpers (2011).

Table 10. Results of statistical analysis on Pijpers (2011) data; in the as-welded condition.

	Slope	$\Delta\sigma_{mean}$	$\Delta\sigma_c$	Number of specimens
Weld toe cracks in cast steel parts	-2.65	165	86	7
	-3.00	174	105	7

Figure 12 shows the comparison between the fatigue strength curves of the weld toe cracks in the cast steels side of the repaired specimens and specimens in the as-welded condition. The fatigue strength curves with the free slope show slight deviation due to different slope values. The fatigue strength curve of the repaired specimens with the fixed slope m=-3 shows a good agreement with the fatigue strength curve in the as-welded condition with the fixed slope of m = -3. At $2{\cdot}10^6$ cycles, the fatigue strength for the fixed slope of m = -3 is 105 MPa and 86 MPa for the free slope of m = -2.65. In accordance with this, the fatigue strength of the fatigue damaged connection made of cast steels can be recovered with the established repair procedure.

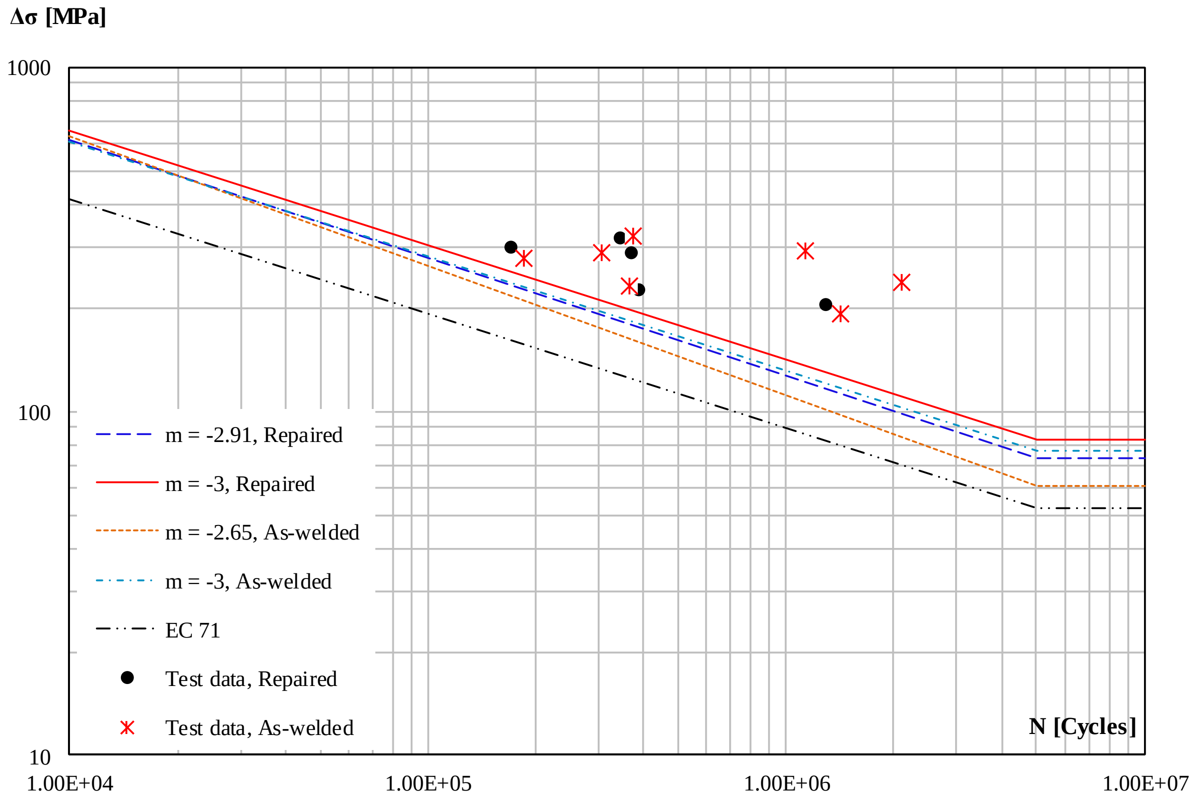


Figure 12. Comparison between S-N curves of weld toe crack in cast steels of repaired and in the as-welded specimens.

5.2. Base material cracks

Base material cracks in rolled steel

Base material cracks in rolled steel were observed in the majority of the test specimens containing S890. Using visual inspection, very highly corroded areas have been observed at the crack initiation locations (see Figure 13). It is assumed that the corrosion pits at the surface of the specimens caused the crack initiation. The base material failures were observed after the repair of the cracks in the welded connections. Therefore, the number of cycles at the crack creation stage is also included in the number of cycles at failure of specimens during the statistical analysis. The results of the statistical analysis on the base material failure in the rolled steel are given in Table 11.

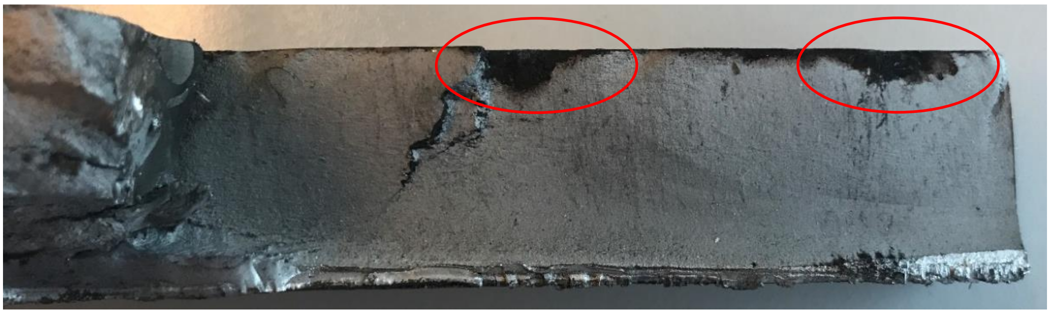


Figure 13 Highly corroded areas at the crack initiation locations on the fracture surface of base material failure in S890.

Table 11. Results of statistical analysis on the base material cracks in rolled steel.

	Slope	$\Delta\sigma_{mean}$	$\Delta\sigma_c$	Number of specimens
Base material cracks in rolled steel	-4.77	265	246	10
	-3.00	234	197	10

Figure 14 compares the fatigue strength curves of the base material cracks in S890 rolled steel with the detail category 125 of EN 1993-1-9 (2006) which is recommended for the fatigue design of the base material. The design curve of EN 1993-1-9 (2006) is found to be conservative. The fatigue strength at $2{\cdot}10^6$ cycles is 197 MPa for the fixed slope of m = -3 and 246 MPa for the free slope of m = -4.77.

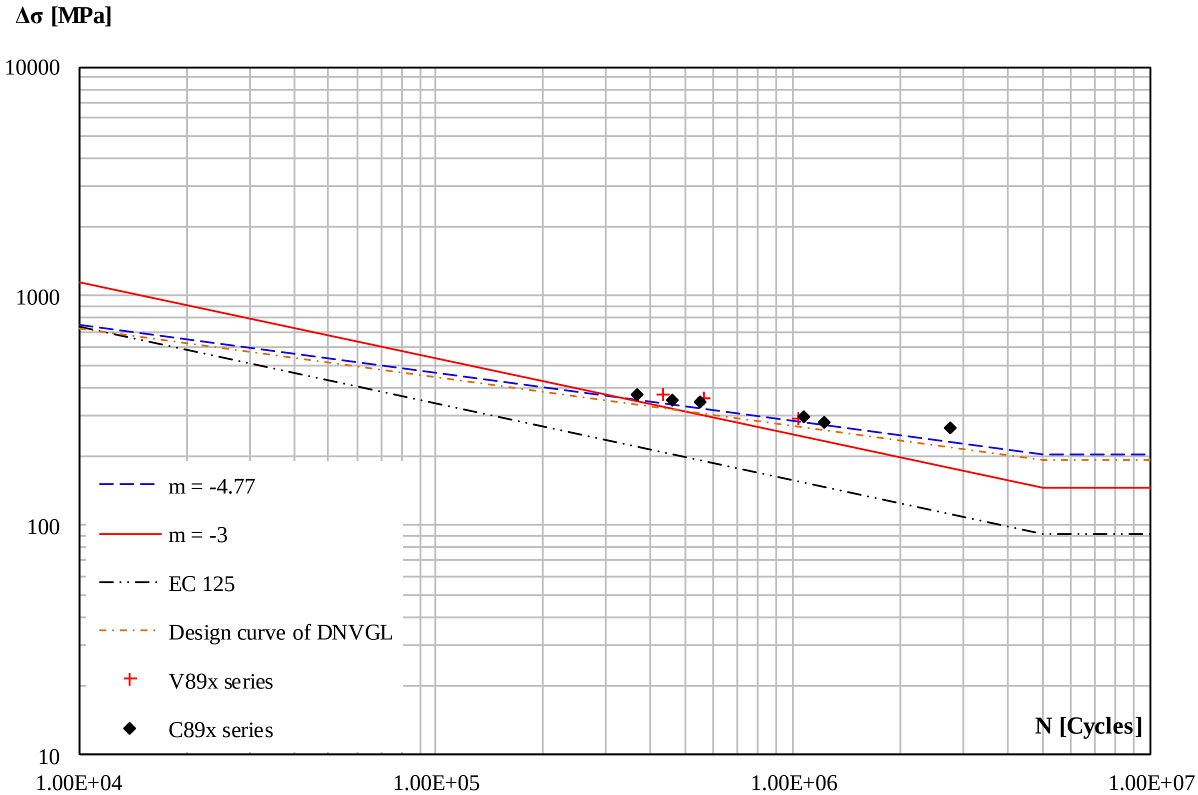


Figure 14. S-N curves of base material cracks in rolled steels of the repaired V-shape welded specimens.

In EN 1993-1-9 (2006), no distinction is made between the fatigue strength of various steel grades and the given design curves are also used for the fatigue design of steels with the yield strength up to 700 MPa. However, DNVGL-RP-C203 (2016) proposes a fatigue design curve for the base material of high strength steels with yield strength above 500 MPa. The design curve has a slope m = -4.7 and the characteristic stress range value at 2 million cycles $\Delta\sigma_c$ = 235 MPa. Figure 14 additionally compares the fatigue strength curve of the base material crack in S890 rolled steel with the design curve of DNVGL-RP-C203. The fatigue strength curve with the free slope exactly matches with the design curve and the slope of the design curve, m = -4.70 is very close to the slope of the fatigue strength curve of the test data, m = -4.77.

Base material cracks in cast steels

In the repaired hybrid specimens, the fatigue cracks were observed in the base material of G10MnMoV6-3 and G18NiMoCr3-6 cast steel grades. Internal imperfections were detected at the crack initiation region of these specimens (see Figure 15). The test data from both cast steel grades were combined and the statistical analysis performed on the test data with the inclusion of the number of cycles at the fatigue crack initiation. From the collected data, it can be seen that the base material failure of all these specimens took place at a similar stress range and number of cycles at fracture, which makes it difficult to determine a free slope for the data scatter. For this reason, the emphasise was put on the fatigue strength curves with the fixed slope m =- 3. The results of the statistical analysis are given in Table 12.

Figure 15 Internal imperfection at the crack initiation location of the base material failure in cast steels.

Table 12. Results of statistical analysis on the base material cracks in cast steels.

	Slope	$\Delta\sigma_{mean}$	$\Delta\sigma_{c}$	Number of specimens
Base material cracks in cast steels	-3.00	220	185	5

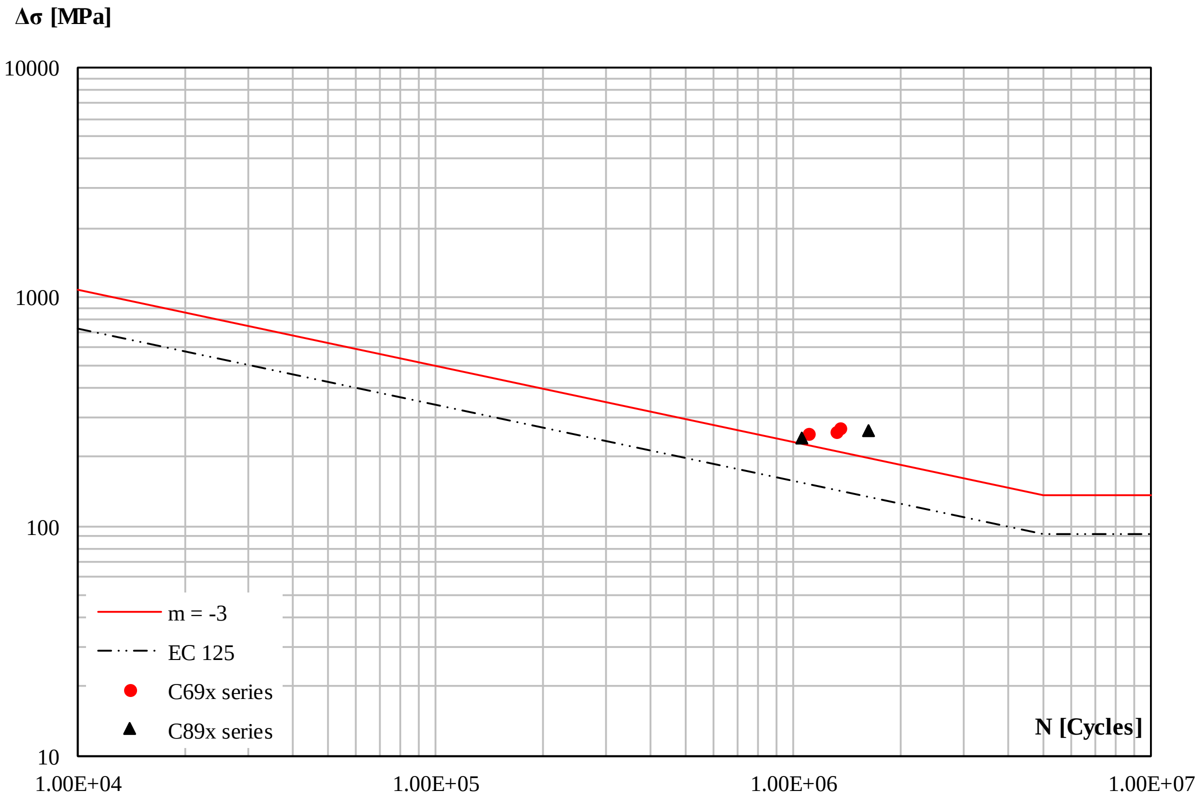


Figure 16. S-N curves of base material cracks in cast steels of the repaired V-shape welded specimens.

Figure 16 presents the fatigue strength curve of the base material cracks in the cast steels compared to the detail category 125 of EN 1993-1-9 (2006). The fatigue strength curve of the test data is located at the above of the design curve of EN 1993-1-9 (2006), which means that the design curve is conservative. The fatigue strength at $2 \cdot 10^6$ cycles is 185 MPa for the fixed slope of m = -3.

EN 1993-1-9 (2006) states that the standard is applicable for structural steels and no distinction is made for rolled and cast steel grades. However, DNVGL-RP-C203 recommends the design curve C for the fatigue design of the base material of cast nodes. The design curve C is identical with detail category 125 of EN 1993-1-9 (2006). In accordance with this, the fatigue strength of the base material in the tested cast steels complies with the requirements of DNVGL-RP-C203 (2016).

6. Conclusions

Within the current study, first V-shape welded specimens made of very high strength rolled and cast steels have been exposed to fatigue loading to create fatigue cracks at the weld toe of the connections. Thereafter, the fatigue damaged welded connections were repaired by welding and the repaired specimens were tested under the same condition of the fatigue crack creation stage. The results of the fatigue tests on the repaired V-shape welded connections lead to following conclusions:

- The fatigue strength of fatigue damaged welded connections can be recovered by the established repair procedure. The effects of stress history are eliminated.
- The fatigue strength curves of the repaired V-shape welded specimens satisfy the requirements of the detail category 71 of EN 1993-1-9 (2006). The test results indicate considerably higher fatigue strength than the detail category.
- The fatigue cracks initiated at the weld toe of the repair weld. This is achieved with the HiFIT treatment of the weld toe of the original weld. Accordingly, the HiFIT is an effective method to eliminate the influence of the loading history before the repair.
- In general, it is assumed that the quality of repair welds is lower than the quality of the original weld. However, in the current study, there was one run-out specimen during the fatigue cracks creation stage and three additional run-outs after the repair. This means that a repaired weld can even be better than the original weld.
- The fatigue strength of the V-shape welded connections is not influenced by additional thermal cycles of the repair weld.
- The fatigue strength curves of the base material failures meet the requirements of the detail category 125 of EN 1993-1-9 (2006) and the recommended design curve of DNVGL-RP-C203.
- The design curves of EN 1993-1-9 (2006) seem to be conservative for the welded connection made of very high strength steels and as well as for the base material.

7. Acknowledgement

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