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Influence of material anisotropy on fatigue crack growth in C-Mn steels of existing structures

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Author contribution statement

H.M. Slot, M.P. Nicoreac, and J. Maljaars contributed equally to the design of the research, to the analysis of the results and to the writing of the manuscript.

Keywords

anisotropy, Charpy-V, crack growth rate, Paris equation, multi-axial fatigue.

Abstract

Rolled steel plates and sections are often applied in structures in such a way that the principal load direction corresponds with the rolling direction. Examples are beams, arches, or pylons of bridges, supporting beams of ship decks, and the main elements of crane structures. However, some types of structure are subjected to a multiaxial stress state or are loaded with the main load direction perpendicular to rolling. The orientation may influence the mechanical properties. This paper studies the influence of anisotropy observed in the microstructure of rolled C-Mn steels on the tensile properties, Charpy impact values and particularly the fatigue crack growth rates. The influence of anisotropy is determined through tests performed at different orientations with respect to the rolling direction, namely L-T, T-L and T-S orientations. Samples were taken from structures that were constructed between 25 to 50 years ago from steel grades Fe510C or St52.3 (modern equivalences S355J2 or S355N). The orientation appears to have a statistically relevant influence on Charpy impact value and fatigue crack growth rate. The anisotropy ratio, defined as the ratio between the mechanical property in a certain orientation with that of the L-T orientation, ranged between 0.30 and 0.53 for Charpy impact values. The anisotropy ratios appear correlated with the absolute Charpy value, with a correlation coefficient of $\rho = -0.8$. The anisotropy ratios of the crack growth in T-L and T-S orientations were 1.19 and 0.43, respectively. Anisotropy ratios for crack growth appear uncorrelated with anisotropy ratios for Charpy impact. The observed

anisotropy may partially explain the difference between uniaxial and multiaxial fatigue crack growth as determined by others.

Nomenclature

$A_{x,TL}$ = anisotropy ratio for property x in T-L orientation

$A_{x,ST}$ = anisotropy ratio for property x in S-T orientation

A_5 = elongation at fracture

a = crack length

a_0 = initial notch depth

B = specimen thickness

b = fatigue strength exponent in the Coffin-Manson equation

C = constant in the Paris relation

$\bar{C}$ = mean constant in the Paris relation

$C_{V,B}$ = Charpy impact value of specimen with thickness B

$C_{V,10TWI}$ = equivalent Charpy impact value for thickness of 10 mm according to the TWI formula

c = fatigue ductility exponent in the Coffin-Manson equation.

da/dN = fatigue crack growth rate

E = Young's modulus.

e = correction for the degrees of freedom of the t-student distribution

f = frequency

G_{ISO} = ferrite grain size according to ISO standard

K = stress intensity factor

m = exponent in the Paris relation

$\bar{m}$ = mean exponent in the Paris relation

n = number of tests

n_i = number of data in group i

n' = cyclic strain hardening coefficient

p = probability

R = stress ratio

R_m = ultimate tensile strength

$R_{p0.2}$ = yield stress

T = temperature

t = plate thickness or value of the two-sided t-student distribution

V = coefficient of variation

W = specimen width

Y = correction factor for the crack length and specimen geometry

ΔK = stress intensity factor range

ΔK_{th} = Threshold stress intensity range

ΔS = stress range

δ^* = length of the fracture process zone.

ϵ'_f = fatigue ductility coefficient in the Coffin-Manson equation

μ = mean

μ_i = mean of $\bar{C}$ for data group i

ρ = correlation coefficient

σ = standard deviation

σ_i = standard deviation of $\bar{C}$ for data group i

σ'_f = fatigue strength coefficient in the Coffin-Manson equation

$\psi(n')$ = function depending on the cyclic strain hardening coefficient (n')

1 Introduction

It is well-known that the microstructure of hot rolled C-Mn steel plates and sections is anisotropic. This is the result of work done during the rolling process, which influences grain size dimensions and dislocations. In addition, rolling causes manganese segregation, resulting into ferrite/pearlite banding in the microstructure of C-Mn steels [1]. It may therefore be possible that the mechanical properties, such as the fracture toughness and crack growth rate, depend on the orientations of the load and of a (potential) crack relative to the rolling direction. However, mechanical properties are usually tested in one orientation only, being the L-T orientation as indicated in Figure 1, i.e. a specimen loaded parallel to the rolling direction with a through-thickness crack perpendicular to the rolling direction. Depending on the delivery conditions, steel suppliers may guarantee the Charpy-V impact energy in this orientation. Yield stress and strain at fracture may also be guaranteed with the load applied in rolling direction. In addition, a certain strain at fracture in thickness direction (z-value) may be guaranteed to limit the influence of possible segregation on lamellar tearing, but Charpy-V tests are usually not done in other orientations than L-T.

Figure 1. Nomenclature for crack growth directions in fracture mechanics specimens, according to [1].

Fatigue tests to determine the crack growth rate are predominantly carried out in L-T orientation and sometimes in L-S orientation. The standard work of King [3] evaluated all tests available at that time without considering the tested crack plane orientation. The leading standard for fatigue crack growth assessments of steels, the British Standard BS7910:2015 [4], is based on [3] and it gives fatigue crack growth rates independent of growth direction. Hence, the rates provided in that standard are expected to predominantly represent L-T orientation.

In practice, plates and sections are often loaded in rolling direction with a potential site of crack oriented perpendicular to the loading direction. Fracture toughness and crack growth rate in L-T and L-S orientation are proper data for estimating the (remaining) fatigue life in these cases. However, different loading or crack orientations are regularly encountered. As an example, ship hulls and orthotropic bridge decks are loaded in multiple directions and the stringers are oriented parallel to the rolling direction. These structures have demonstrated to be sensitive to fatigue cracking. Cracks in bridge deck plates are regularly observed starting at the weld with the dominant stress direction perpendicular to the rolling direction, see [5], [6] (Figure 2). The T-L and T-S crack plane orientations are governing in such cases. The data obtained from L-T orientation may be inappropriate for assessing the (remaining) fatigue life, i.e. anisotropy may have an important effect.

Figure 2. Typical deck plate crack in orthotropic bridge decks: crack plane parallel to rolling, stress perpendicular to rolling.

The microstructural orientation is unknown in other applications. Examples are cover plates in riveted joints of existing bridges, where multiple operations such as cutting and drilling were applied and the microstructural orientation was not checked before it was applied in the structure. Riveted joints in bridges are prone to fatigue failure, [7].

Crack growth under multiaxial fatigue loading has been the subject of many studies. In these cases, once a crack has initiated, the orientation of the crack is often inclined to the rolling direction. The influence of material anisotropy may be relevant in these cases.

Literature into fatigue crack growth properties of C-Mn steels in different crack plane orientations is scarce. Heiser and Hertzberg [8] tested the fatigue crack growth rates for three orientations – L-T, T-S, and S-L – of hot rolled steel plates with a yield stress of 372 MPa

and with ferrite/pearlite banding in the microstructure containing (wt %): 0.23C, 1.43Mn, 0.1Cr, 0.1Ni and 0.023Al. The dependence of the crack growth rate on the stress intensity factor range (ΔK) was shown to be sensitive to the microconstituents present and their orientation relative to the fracture plane. The fatigue crack growth rate (da/dN) in T-S orientation was a factor 2 to 4 higher than in L-T orientation for $10 \leq \Delta K/\text{MPa}\sqrt{\text{m}} < 20$, but lower for $\Delta K > 35 \text{ MPa}\sqrt{\text{m}}$. Ohji et al [9] made a distinction between two microstructure related sources for anisotropic fatigue crack growth behaviour: 1) the laminated microstructure, and 2) the inclusions present in the structure, of rolled steel plate. They prepared two groups of steel: 1) by annealing and 2) a spheroidizing treatment, so that the effects of the laminated microstructure and the mechanical fibering of inclusion, both of which were produced by rolling, could be separated. The fatigue crack growth rates was much more depending on the orientation in the annealed temper than with the spheroidized temper. They concluded that the anisotropy in the behaviour of fatigue crack growth was primarily affected and controlled by the laminate microstructure, while the inclusions gave only a secondary effect.

The current paper determines the influence of the anisotropy of the microstructure on mechanical properties by performing tensile tests, Charpy impact tests, and crack growth tests, in various crack plane orientations, namely L-T, T-L and T-S. Samples were taken from structures that were constructed between 25 to 50 years ago from steel grades that are equivalent to modern grades S355J2 or S355N. This material is selected because many fatigue critical structures have been constructed from this or from similar materials. Microstructural anisotropy may be less apparent in the heat affected zone in welded structures as compared to parent metal. The experimental study is, however, limited to parent metal. This is relevant because flaws can only be detected with sufficient reliability once they have reached a certain depth, which is often larger than the depth of the HAZ in fillet welded joints, as applied in bridge decks and ship hulls.

Results are presented as anisotropy ratio, which is defined as the ratio between the value of a certain mechanical property in a certain orientation and the value of that property in the L-T orientation. Thus for property x in T-L orientation:

$$A_{x,TL} = \frac{x_{T-L}}{x_{L-T}} \quad (1)$$

and for property x in S-T orientation:

$$A_{x,ST} = \frac{x_{S-T}}{x_{L-T}} \quad (2)$$

where x_{a-b} is property x tested in orientation a-b.

2 Experimental program

Samples were taken from deck plates of five bridges that were constructed between 25 to 50 years ago. The plate thickness was $t = 10$ mm for three of these deck plates and $t = 12$ mm for two deck plates. The plates were constructed from C-Mn steels designated as Fe510C or St52.3 following [10]. The modern equivalent to these steel types is S355J2, according to [11], and they contain a maximum of 0.20 wt % C and a maximum of 1.6 wt % Mn. The samples were taken remote from the load positions in service, at locations where the stress ranges remained negligibly low. The samples were also taken remote from welds and heat affected zones.

Microscopy images were taken to characterize the microstructure of each sample. The ferrite grain size was determined in accordance with [12]. The chemical composition was obtained through Optical Emission Spectrometry (OES). Two standardized tensile tests per sample were performed in rolling direction, L-T, and in addition two tensile tests per sample were performed perpendicular to the rolling direction, in plane of the plate, T-L.

Charpy-V impact tests were performed on each sample at test temperatures of -20 °C and +15 °C for crack plane orientations L-T and T-L. In addition, one sample was tested in orientation T-S. Three, six or nine Charpy values were performed for each combination of sample, test temperature, and orientation. Sub-size specimens with a thickness of 7.5 mm were applied for the samples with a plate thickness of 10 mm. The test results of the sub-size specimens with a specimen thickness of 7.5 mm were scaled to the standard thickness of 10 mm using [13]:

$$C_{V,B} = C_{V,10TWI} \frac{B}{10 \text{ mm}} \frac{1 + \frac{1}{2} \exp\left(\frac{2}{17.3} \left[\frac{C_{V,10TWI} \cdot \text{mm}}{B} - 44.7\right]\right)}{1 + \exp\left(\frac{2}{17.3} \left[\frac{C_{V,10TWI} \cdot \text{mm}}{B} - 44.7\right]\right)} \quad (3)$$

where $C_{V,B}$ is the Charpy impact value of the sub-size specimen with thickness B and $C_{V,10TWI}$ is the equivalent Charpy impact value for a standard specimen with thickness 10 mm.

Fatigue crack growth tests were performed according to [14] on specimens manufactured from two of the five samples, being the two samples with the lowest upper shelf Charpy-V impact values in the transverse direction (T-L). Standard four point single edge notch bend (SENB4) specimen [14] were tested at air temperature of +15 °C in L-T orientation (crack grows perpendicular to rolling direction) and T-L and T-S orientations (crack grows parallel to rolling direction). Three or four tests were performed for each combination of sample and orientation.

The test procedure consisted of a force controlled constant amplitude loading, following a K -increasing test procedure according to [14]. The tests were carried out in force control with a stress ratio $R = 0.1$, a frequency of $f = 5$ to 7 Hz and an environmental temperature of $T = 15$ °C. The dimensions of the specimens for the crack growth tests were limited by the nominal thickness of the deck plates. Table 1 gives specimen dimensions as function of the crack plane orientation.

Table 1. Specimen dimensions for fatigue crack growth tests as function of the crack plane orientation.

Orientation	$B^a)$	$W^a)$	S [mm]	D [mm]
L-T and T-L	$t - 1 \text{ mm}$	$2B$	160	80
T-S	$2W$	$t - 1 \text{ mm}$	160	80

^{a)} t = sample thickness, equal to 10 mm for sample A and 12 mm for sample B

The specimens were manufactured with a V-notch, the machined notch length $a_n = 1.0$ or 1.5 mm, and an angle of 60° [14]. Crack gauges were attached to both sides of the specimens in the expected crack path for crack growth monitoring. Crack gauges TK-09-

CPB02-005/DP and TK-09-CPA01-005/DP were used with 10 gridlines spaced 0.25 mm and 20 grid lines spaced 0.25 mm, respectively.

The specimens for the L-T and T-L orientations ($W = 2t - 1$) were pre-cracked with an initial load (P_{max}) equal to the test loading. A crack extension $\Delta a = a_p - a_n = 0.90$ mm was realized before the crack growth measurements were started. The relative crack size at the start of the crack growth test was $a_p/W = 0.04$. The specimens for the T-S orientation ($W = t - 1$) were pre-cracked with an initial load (P_{max}) that was 10% higher than the test loading. The load was decreased to the test load after a crack extension $\Delta a = a_p - a_n = 0.4$ mm and an additional crack extension of 0.5 mm was realized before the crack growth measurements were started. The relative crack size at the start of these tests was $a_p/W = 0.08$.

3 Experimental results

Table 2 gives the chemical compositions of the five samples, including the requirements for S355J2 [11] and S355N [15]. All samples meet the requirements for their modern equivalents S355J2 and S355N, with the exception of sample A that has a sulphur content slightly higher than the allowed maximum of 0.025% and an aluminium content lower than the required minimum of 0.015%. Figure 3 presents the microstructure of the samples (at different magnification factors). It shows that the microstructures of all samples contain bands of fine ferrite and pearlite colonies that are common for C-Mn steels, [1]. The ferrite grain size (G_{ISO}) was determined from the microstructures and is given in the last column of Table 2. All samples have a relatively fine grain structure with a grain size between 9.0 and 10.5. For comparison, [15] requires a grain size $G_{ISO} \geq 6$ for S355N.

Table 2. Chemical composition (wt %) and grain size.

Sample	C	Si	Mn	P	S	Cr	Ni	Cu	Al _{tot}	Mo	N	G_{ISO} [-]
A	0.14	0.31	1.05	0.02	0.03	0.08	0.15	0.27	0.01			10.3
B	0.17	0.45	1.19	0.020	0.018	0.03	0.03	0.01	0.039	<0.01		9.0
C	0.16	0.34	1.10	0.013	0.010	0.02	0.02	0.02	0.022	0.01		9.0
D	0.17	0.44	1.20	0.02	0.02		0.02	<0.01	-			10.0
E	0.17	0.47	1.44	0.02	<0.01			0.02	-			10.5
Required												
S355J2 ^{a)}	<0.20	<0.55	<1.60	<0.025	<0.025	-	-	<0.55				
S355N ^{b)}	<0.22	<0.55	0.85-1.75	<0.035	<0.030	<0.35	<0.55	<0.60	>0.015	<0.13	<0.017	≥6

a) S355J2 according to EN 10025-2 [11]; b) S355N according to EN 10025-3 [15].

Figure 3. Microstructures of samples A to E and detail of sample B showing an elongated MnS inclusion (note: different magnification factors).

Table 3 summarizes the tensile test results of the five samples. The mean values from two tests are listed for the yield stress ($R_{p0.2}$), ultimate tensile strength (R_m), and elongation at fracture (A_5). Requirements on the tensile properties in L-T orientation for S355J2 [11] and S355N [15] are equal and are shown for comparison. The table also provides anisotropy ratios as defined by Eq. (1) and (2). The anisotropy ratios for the yield stress ($A_{Rp,TL}$) and tensile strength ($A_{Rm,TL}$) are all close to 1.0, with the largest value of 1.12 observed for the yield stress of sample A. The anisotropy ratios for the elongation at fracture ($A_{A5,TL}$) are all lower than unity and vary between 0.73 and 0.93 with a mean value of 0.86.

Table 3. Tensile tests results.

Sample	Orientation	$R_{p0.2}$ [MPa]	R_m [MPa]	A_5 [%]	Anisotropy ratios [-]		
					$A_{Rp,TL}$	$A_{Rm,TL}$	$A_{A5,TL}$
A	L-T	408	562	28.3			
($t = 10$ mm)	T-L	457	584	26.3	1.12	1.04	0.93
B	L-T	381	524	28.7			
($t = 12$ mm)	T-L	386	523	25.3	1.01	1.00	0.88
C	L-T	360	506	34.0			
($t = 10$ mm)	T-L	367	510	30.7	1.02	1.01	0.90
D	L-T	383	537	25.8			
($t = 12$ mm)	T-L	396	549	18.8	1.03	1.02	0.73
E	L-T	416	585	23.0			
($t = 10$ mm)	T-L	409	577	20.0	0.98	0.99	0.87
Required: S355J2 & S355N	L-T	≥355	470-630	≥22			

¹⁾ S355J2 according to EN 10025-2 [6],

²⁾ S355N to EN 10025-3, [13].

Table 4 summarizes the means (μ) and standard deviations (σ) of the tested number (n) of Charpy-V impact tests, where the test results of the sub-size specimens with a specimen thickness of 7.5 mm are scaled to the standard thickness of 10 mm with Eq. (3). Both sub-sized and standard thickness specimens were tested for sample D, and the results are used to estimate the appropriateness of Eq. (3). The ratio between scaled values and standard specimens, $C_{V10,TWI}/C_{V10}$ is 1.08 on the average, with a standard deviation of 0.14. As a comparison, the coefficient of variation of the individual tests per sample and orientation ranges between 0 and 0.23 (average 0.08) and the average ratio $C_{V10,TWI}/C_{V10}$ is 1 standard deviation from unity. The number of tests appears too small to for a definite conclusion.

The last rows of Table 4 provide the requirements for S355J2 [11] and S355N [15] for reasons of comparison. EN 10025-2 [11] requires a minimum Charpy-V impact value for S355J2 in L-T orientation only, whereas EN 10025-3 [15] provides requirements in L-T and T-L orientations for S355N. All requirements are met, but the Charpy-V impact value in T-L orientation of sample A at +15 °C is only just met. The Charpy-V values at -15 °C and + 20 °C are almost equal for samples A and B, indicating that these are upper shelf values, but these upper shelf values are relatively low.

The last two columns of Table 4 provide the Charpy-V impact value anisotropy ratios for the T-L orientation ($A_{CV,TL}$) and the T-S orientation ($A_{CV,TS}$) as defined by Eqs. (1) and (2), the latter only for sample B. All anisotropy ratios are far below unity, where $0.30 \leq A_{CV,TL} \leq 0.51$, indicating a strong anisotropy effect with Charpy impact energies in T-L and T-S orientation, being significantly lower than in L-T orientation. The anisotropy ratios for sample B for T-L and T-S orientations vary between 0.41 and 0.44. Note that both orientations result in fracture surfaces in the same plane, but that the directions of crack growth are different.

Table 4. Charpy-V impact test results.

Sample	Orientation	Test temp. [°C]	Specimen thickness B [mm]	Charpy-V impact energy [J]				$\frac{C_{V,10TWI}}{C_{V,10}}$	Anisotropy ratios	
				$C_{V,7.5}$ μ	$C_{V,10}$ μ	or $C_{V,10TWI}$ σ n		$\frac{C_{V,10TWI}}{C_{V,10}}$ [-]	$A_{CV,TL}$ [-]	$A_{CV,TS}$ [-]
A ($t = 10$ mm)	L-T	+15	7.5	60.0	80.8	2.3	3			
		-20	7.5	68.3	92.1	7.2	6			
	T-L	+15	7.5	25.8	34.5	3.9	9		0.43	
		-20	7.5	27.3	36.6	3.9	6		0.40	
B ($t = 12$ mm)	L-T	+15	10		114	1.7	3			
		-20	10		101	2.4	6			
	T-L	+15	10		46.7	1.0	6		0.41	
		-20	10		43.3	0.8	6		0.43	
	T-S	+15	10		50.0	1.7	3			0.44
		-20	10		44.0	8.7	3			0.43
C ($t = 10$ mm)	L-T	-20	7.5	99.3	135	14	3			
	T-L	+15	7.5	49.3	66.2	5.1	3			
		-20	7.5	30.3	40.6	2.8	3		0.30	
D ($t = 12$ mm)	L-T	-20	10		68.0	15	3			
	T-L	+15	10		48.0	0.0	3			
		-20	10		36.0	3.0	3		0.53	
	L-T	-20	7.5	61.0	82.2	6.2	3	1.21		
	T-L	+15	7.5	39.0	52.3	0.0	3	1.09		
		-20	7.5	25.0	33.5	4.6	3	0.93	0.41	
E ($t = 10$ mm)	L-T	-20	7.5	111	152	33	3			
	T-L	+15	7.5	60.0	80.8	0.0	3			
		-20	7.5	41.0	55.0	8.4	3		0.36	
Required:										
S355J2	L-T	-20	10		≥27		3			
	T-L	-20	10		-					
S355N	L-T	+15	10		≥53 ^{a)}		3			
		-20	10		≥40		3			
	T-L ^{b)}	+15	10		≥30 ^{a)}		3			
		-20	10		≥20		3			

^{a)} This value is based on linear interpolation between the required values at specified temperatures.

^{b)} This is not a standard requirement, but can be requested in a contract.

Wilson [16] and Ghosh et al. [17] demonstrate that sulphur inclusions as well as shape control of all inclusions in carbon steels have a significant influence on the Charpy impact upper shelf level, especially in the transverse direction. Figure 4 therefore provides the Charpy impact energies as a function of the sulphur content. A relatively strong correlation is indeed observed between the sulphur content and the Charpy-V impact energy, with correlation coefficients $\rho = -0.8$, -1.0 and -0.8 for the tests at $-20\text{ }^{\circ}\text{C}$ in L-T orientation, $+15\text{ }^{\circ}\text{C}$ in T-L orientation, and $-20\text{ }^{\circ}\text{C}$ in T-L orientation, respectively. Because the correlation coefficients in L-T and T-L orientation are almost equal, the anisotropy ratio $A_{CV,T-L}$ is weakly correlated with the Sulphur content ($\rho = 0.5$). A correlation coefficient of $\rho = -0.8$ is obtained between the impact energy in L-T orientation and the anisotropy ratio $A_{CV,TL}$, see Figure 5.

Figure 4. Relation between sulphur content and Charpy-V impact energies: a) L-T orientation; b) T-L and T-S orientation.

Figure 5. Relation between Charpy-V impact energy and anisotropy ratio.

Because of the strong anisotropy in Charpy V impact energies, it is interesting to examine if the same trends are observed in the fatigue crack growth tests. The two samples with relatively low upper shelf Charpy V values – Samples A and B – were selected for the fatigue crack growth tests. The fatigue crack growth data, obtained as crack depth, a , at applied number of cycles, N , are used to determine the crack growth rates da/dN using “secant point-to-point” method according to [14]. The corresponding linear elastic stress intensity factor ranges, ΔK , are obtained from [18]:

$$\Delta K = Y \Delta S \sqrt{\pi a} \quad (4)$$

$$Y = \frac{0.923 + 0.199 \left(1 - \sin \left(\frac{\pi a}{2W} \right) \right)^4}{\cos \left(\frac{\pi a}{2W} \right)} \sqrt{\frac{2W}{\pi a} \tan \left(\sin \left(\frac{\pi a}{2W} \right) \right)} \quad (5)$$

where ΔS is the stress range. Crack gauges were applied at both sides of the specimen. The results are evaluated for each specimen side, as well as for the average of the two sides. Between three and five tests were performed per combination of sample and orientation.

The data of the individual specimen per sample and orientation are pooled and displayed in Figure 6 per side of the specimen (i.e. for each crack gauge) in grey dots and the average of

both sides in black dots. Figure 6(a) and (b) give the test results in L-T orientation of sample A (4 specimen) and sample B (4 specimen), respectively. Figure 6(c) and (d) give the results in T-L orientation of sample A (4 tests) and sample B (3 tests), respectively, and Figure 6(e) gives the results in T-S orientation of deck plate B (3 tests). The crack front was slanted in all tests in T-S orientation of deck plate A, resulting a deviation of the crack growth rates at the two specimen sides that was beyond acceptable according to [14]. These tests are therefore ignored. Regression lines are added to each graph, based on a single stage Paris equation:

$$\frac{da}{dN} = C \cdot \Delta K^m \quad (6)$$

where C and m are calibration variables, with best fit values according to Table 5. The variation in exponent m between the different samples and orientations is small (coefficient of variation, $V = 0.08$). The data are therefore also fit with a mean exponent $\bar{m} = 3.50$. This allows for comparing the corresponding fit values of $\bar{C}$ for different samples and orientations, see the last columns of Table 5.

Figure 6. Fatigue crack growth rates for: (a) Sample A (4 tests) L-T orientation; (b) Sample B (4 tests) L-T orientation, (c) Sample A (4 tests) T-L orientation, (d) Sample B (3 tests) T-L orientation, (e) Sample B (3 tests) T-S orientation.

Table 5. Regression variables of the fatigue crack growth rate, derived with the secant method (average of two sides).

Sample	Orientation	# valid tests	R	m	$\text{Log}_{10}(\bar{C})[\text{MPa}, \text{m}]$		$\text{Log}_{10}(\bar{C})[\text{MPa}, \text{m}]^{\text{a})}$	
					μ	σ	μ	σ
A ($t = 10 \text{ mm}$)	L-T	4	0.1	3.56	-11.84	0.06	-11.76	0.06
	T-L	4	0.1	3.28	-11.36	0.04	-11.64	0.04
	T-S	0						
B ($t = 12 \text{ mm}$)	L-T	4	0.1	3.24	-11.39	0.03	-11.71	0.04
	T-L	3	0.1	3.41	-11.55	0.04	-11.67	0.04
	T-S	3	0.1	2.88	-11.37	0.12	-12.08	0.12

a) Exponent $\bar{m} = 3.50$.

Figure 7 provides all measured data of $\bar{C}$. The figure again demonstrates the differences in crack growth rate between different orientations. Figure 7(a) indicates that the data for sample A in L-T orientation enclosed with a green ellipse in the figure, give lower $\log(\bar{C})$ data than the other data of that same sample and orientation. It appears that the deviating data stem from measurements on one side of one of the specimen. This is possibly due to a measurement inaccuracy of the location of the crack gauge – the test results in terms of $\bar{C}$ are extremely sensitive to the exact location. Irrespective of whether or not this specimen is included in the evaluation, the data demonstrate a large difference between the three tested orientations. A Kolmogorov-Smirnov test [19] is applied to investigate the null hypothesis that the results obtained in different orientations and samples belong to the same distribution. This null hypothesis is rejected with high confidence (more than 99 %) for any combination of orientations (L-T, T-L and T-S). However, this test also rejects the hypothesis that different specimens from the same batch belong to the same distribution and hence it is considered too strict for the current fatigue application. In fatigue, testing the hypothesis of similarity is often done through an F-test that considers if the standard deviations are similar, and the following test to investigate if the means are similar (see [20], [21], [22]):

$$|\mu_1 - \mu_2| = t \sqrt{\left(\frac{1}{n_1} + \frac{1}{n_2}\right) \frac{(n_1 - e)\sigma_1^2 + (n_2 - e)\sigma_2^2}{(n_1 - e) + (n_2 - e)}} \quad (7)$$

where:

μ_i = mean of $\bar{C}$ for data group i .

σ_i = standard deviation of $\bar{C}$ for data group i .

n_i = number of data in group i .

t = value of the two-sided t-student distribution at p significance and $(n_1 - e) + (n_2 - e)$ degrees of freedom.

e = correction for the degrees of freedom of the t-student distribution, in this case $e = 2$ because two parameters ($\bar{m}$ and $\bar{C}$) were used to fit the data.

Figure 7. Distribution of $\log_{10}(\bar{C})$ for a fixed slope $\bar{m} = 3.50$: (a) Individual data as function of ΔK ; (b) Empirical cumulative distributions.

These tests again reject the null hypothesis with 99 % or higher significance for any combination of orientations (L-T, T-L and T-S), irrespective of whether or not the deviating specimen data of sample A in L-T orientation is considered.

Table 6 provides the crack growth rate anisotropy ratios, which are determined on the basis of $\bar{C}$ for a fixed slope $\bar{m} = 3.50$. The anisotropy ratios $A_{cg,T-L}$ are of similar magnitude for the two samples and they demonstrate an average 18 % to 22 % higher crack growth rate in T-L orientation as compared to L-T orientation. The results in T-S orientation, however, show

a completely different trend, where the average crack growth rate is more than two times lower, but the scatter is approximately two times higher than in L-T orientation.

Table 6. Anisotropy ratios of mean values of variable $\bar{C}$ in the fatigue crack growth rate.

Sample	$A_{C,TL}$ [-]	$A_{C,TS}$ [-]
A ($t = 10$ mm)	1.33 ^{a)}	-
B ($t = 12$ mm)	1.11	0.42

^{a)} Equal to 1.24 if the test of the specimen in L-T orientation with deviating growth rate is ignored.

BS 7910 [4] provides the mean (μ_{BS}) and mean plus two standard deviations ($\mu_{BS} + 2\sigma_{BS}$) crack growth relations for structural steels. Note that σ_{BS} reflects the variation in the average growth rate between samples and steels, not the variation within a test. This is because the standard is aimed for assessing the number of cycles required for growth from a certain initial crack to a critical one, and temporary crack retardation and acceleration is in that case of less importance if it is assumed that these influences counterbalance and therefore neutralize each other. Hence, the mean regression curves from the tests should be compared to μ_{BS} and $\mu_{BS} + 2\sigma_{BS}$ of BS 7910 in Figure 6. Table 7 provides the average crack growth rate per specimen for a fixed exponent of $\hat{m} = 2.88$ – equal to the slope of BS 7910 for $\Delta K > 10$ MPa $\sqrt{m}$ – and it gives the difference with BS 7910 in terms of standard deviation. The crack growth rates of the tests in L-T and T-L are respectively 1.1 and 1.9 standard deviations above the mean of BS 7910, whereas the crack growth rates in T-S orientation are 2.5 standard deviations below the mean of BS 7910. Expressed differently, the mean crack growth rates of the tests in L-T, T-L and T-S orientations are approximately 13 % higher, 23 % higher and 30 % lower than the mean in BS7910, respectively. These anisotropic differences are substantial in terms of fatigue life.

Table 7. Mean crack growth rates per test (average of two sides) compared to BS7910 [4].

Sample	Orientation	$\text{Log}_{10}(\dot{C})[\text{MPa}, \text{m}]^{\text{a)}}$	
		μ	$(\mu - \mu_{BS})/\sigma_{BS}$
A ($t = 10 \text{ mm}$)	L-T	-10.92; -10.93; -11.04 ^{b)} ; -10.94	1.41; 1.26; 0.35 ^{b)} ; 1.21
	T-L	-10.85; -10.82; -10.89; -10.84	1.96; 2.27; 1.66; 2.05
	T-S	-	-
B ($t = 12 \text{ mm}$)	L-T	-10.94; -10.96; -10.91; -10.95	1.21; 1.03; 1.47; 1.10
	T-L	-10.87; -10.85; -10.92	1.83; 2.01; 1.40
	T-S	-11.39; -11.25; -11.45	-2.68; -1.48; -3.22

^{a)} Exponent $\hat{m} = 2.88$, equal to BS7910 [4].

^{b)} Test with deviating crack growth rate measured at one side of the specimen.

4 Discussion

The Charpy impact energy appeared strongly related to the crack plane orientation. This is attributed to the orientation of the elongated MnS inclusions that can be observed in Figure 3. This corresponds with the observations of Ghosh et al. [17], who reported on the role of crystallographic texture on Charpy impact properties. The Charpy values appeared correlated with the sulphur content, as in [16]. Kotrechko et al. [23] demonstrated that the non-uniform distribution of crystallographic planes due to the presence of strong crystallographic texture can cause anisotropy in Charpy impact properties. High intensity of certain texture components have been reported to induce anisotropy, [24]. Literature into this subject is scarce and scattered, and further research is required to explain the anisotropy in the (upper shelf) Charpy impact values.

In agreement with [16] and [17], the tested Charpy impact energies in T-L and T-S orientations were significantly lower as compared to L-T orientation, whereas standards require a minimum value in L-T orientation only (with at most an optional requirement in T-L orientation, for certain qualities only). If structures are loaded transverse to the rolling direction, it is important to obtain ductile fracture behaviour in T-L and T-S orientations. The authors therefore consider it important to put forward requirements in standards on minimum Charpy impact energies in T-L and T-S orientations.

The fatigue crack growth specimen dimensions of sample B in T-S orientation and in L-T and T-L orientations were $W \times B = 11 \text{ mm} \times 22 \text{ mm}$ and $W \times B = 22 \text{ mm} \times 11 \text{ mm}$, respectively, see Table 1. The influence of specimen thickness (B) on the results is expected to be negligible and this cannot explain the differences observed in the crack growth rates.

Examination of the fracture surfaces of the fatigue tests provided insight into the reason for the observed anisotropy. Figure 8 shows the fracture surfaces of sample B for crack plane orientations T-L and T-S. The rolling direction (indicated by the red arrows) is perpendicular and parallel to the crack front for the T-L and T-S orientations, respectively. The fracture surfaces of the fatigue crack (and also of the residual ductile failure) show clear “lines” and signs of micro-delamination of a layered microstructure. The metallographic picture of plate B in Figure 3 confirms this layered structure. It is expected that these layers with a strong anisotropic nature act as temporary fatigue crack arrestors in T-S orientation. The purple arrows in Figure 8 depict some of the observed distinct “steps” or “crack arrestors” in the fracture surface.

Figure 8. Fracture surfaces of fatigue crack growth specimens from sample B: (a) In T-L orientation; (b) In T-S orientation, with purple arrows indicating “steps” or “crack arrestors”.

Figure 9 shows SEM pictures of the fracture surfaces with different levels of magnification (x250, x1.50k, x5.00k). The left and right columns of the figure show pictures of the T-L and T-S orientation, respectively. The detailed pictures were taken just above the final fatigue crack front, indicated with the boxes in the first row of pictures. The SEM pictures with a magnification of x250 (second row of pictures in Figure 9) confirm the mentioned layered microstructure and micro-delamination in the fracture surfaces parallel to the rolling direction of the plate. The fatigue fracture surface of the T-S orientation (magnifications x1.50k, x5.00k in the right column of Figure 9) contains substantially more small secondary cracks perpendicular to the primary crack growth direction and parallel to the rolling direction than the fatigue fracture surface of the T-L orientation (see same magnifications in left column). Further, the striations in the fracture surface of the T-S orientation often deviate, in the crack plane, with a small angle from the primary crack growth direction. In this T-S orientation there were certain “crack arrests” along the crack front. This small angle suggests that the local crack front did not start at the same time after passing a certain crack arrest layer in the microstructure. In addition to some MnS stringer crack arrestors, the interfaces between the ferrite and perlite seem to be the most frequently occurring crack arrestors in this microstructure. Nevertheless, the striations observed in the perlite are parallel to each other and show the same spacing, thus constant fatigue crack growth rate.

These mechanisms were not observed in the fatigue fracture surface of the T-L orientation. The observed mechanisms in the fatigue crack growth in the T-S orientation, being the small secondary cracks perpendicular to the primary crack growth direction and the inclination of most striations, suggest that more mechanical work must be done for a certain amount of crack extension as compared to the T-L orientation. It explains the lower mean crack growth rate in the T-S orientation. The temporary crack arrestors further explain the more scattered crack growth rate. The random nature of these temporary crack arrestors may also explain the unequal and irregular growth of both sides of the sample A specimens tested in T-S orientation.

Figure 9. SEM pictures of fracture surfaces of specimens from deck plate B: (a) In the left column for the T-L orientation; (b) In the right column for the T-S orientation.

The difference in crack growth rates between L-T and T-S orientations in this research provide a is larger than observed in [8] for the treatment “Pearlite-ferrite (banded) - P-F”. As already mentioned, the fatigue crack growth rate in T-S orientation in that paper was a factor 2 to 4 higher than in L-T orientation for $10 \leq \Delta K < 20$, but lower for $\Delta K > 35 \text{ MPa}\sqrt{\text{m}}$.

A microstructural anisotropic difference with respect to layered orientation as observed between T-S and T-L orientations was not observed and is not to be expected between T-L and L-T orientations. The crack growth rate anisotropy ratios evaluated in terms of $\bar{C}$ were also closer to unity for T-L orientation as compared to T-S orientation. Yet, the statistical tests demonstrate that the difference in rate between the T-L and L-T orientation is also statistically relevant. A possible explanation for this difference is the observed anisotropy in the tensile test properties. Ellyin [25] presented a low-cycle fatigue based crack propagation model. The result of his derivation is:

$$\frac{da}{dN} = 2\delta^* \left[\frac{\Delta K^2 - \Delta K_{th}^2}{4E\sigma_f'\epsilon_f'\delta^*\psi(n')} \right]^{-1/(b+c)} \quad (8)$$

where

ΔK_{th} = Threshold stress intensity range.

E = Young's modulus.

σ_f' = Fatigue strength coefficient in the Coffin-Manson equation.

ϵ_f' = Fatigue ductility coefficient in the Coffin-Manson equation.

b = Fatigue strength exponent in the Coffin-Manson equation.

c = Fatigue ductility exponent in the Coffin-Manson equation.

δ^* = Length of the fracture process zone.

$\psi(n')$ = function depending on the cyclic strain hardening coefficient (n').

The fatigue strength coefficient (σ'_f) is correlated to the tensile strength (R_m), whereas the fatigue ductility coefficient (ϵ'_f) is related to the elongation at fracture (A_5), [26]. This correlates the anisotropy ratio for the crack growth rate in T-L orientation to the anisotropy ratio of the tensile test properties. The tested anisotropy ratios for the tensile strength ($A_{Rm,TL}$) were close to 1.0. The anisotropy ratios for the elongation at fracture ($A_{A5,TL}$) vary between 0.73 and 0.93 with a mean of 0.86. Following Ellyin's model, these tensile test anisotropy ratios may explain the crack growth rate anisotropy ratio as observed for crack plane orientation T-L of approximately 1.2. The lower elongation at fracture in T-L orientation as compared to L-T orientation was already observed in [27], and attributed to inclusions that are originally spheroidal of shape, but that are distorted in the principal working direction during rolling if they are softer and more ductile than the matrix.

This study clearly showed that the fatigue crack growth rate anisotropy ratios are not correlated to the Charpy-V impact anisotropy ratios: The resistance against impact fracture was lower in T-L and T-S orientations as compared to L-T orientation, whereas the resistance against fatigue cracking was lower in T-L orientation, but higher in T-S orientation as compared to L-T orientation. Walters et al. [28] observed a dependency of the crack growth rate on the fracture toughness (and Charpy-V impact energy) in S460 steel. The difference with the current study is that the dependency of crack growth rate in [28] was observed at temperatures below the brittle to ductile transition temperature. Micro cleavage cracking and micro-void coalescence may have influence the fatigue crack growth rate in that range. The tests in the current study were carried out in the upper shelf range – although the upper shelf Charpy value was low especially for sample A. The fracture surfaces did not show any signs of cleavage. Indeed, [28] also shows no influence of temperature on the crack growth rate above the transition temperature. To summarize, brittle impact fracture is based on a different metallurgical failure mechanism as compared to ductile fatigue crack growth.

A relatively large number of scientific studies have been devoted to multi-axial fatigue crack growth. Due to the loading conditions applied in these studies, cracks usually grow in a plane that is not perpendicular to the rolling direction. Material anisotropy may be important in these cases, but is usually not considered explicitly as a variable. Two studies are evaluated here to demonstrate the significance. Murakami et al. [29] determined the crack path from specimens that were loaded with a combined bending and torsion fatigue load. The specimens tested in phase developed a mode I fatigue crack with a path that deviated

from the plane perpendicular to the principal stress. The cracks initially followed the plane of maximum shear stress but eventually approached the plane normal to the direction of the maximum principal stress. The figures presented in that paper show that the surface crack had an orientation inclined from the plane perpendicular to the principal stress with approximately 5° towards the T-L plane. The current paper shows that the crack growth rate in T-L orientation is higher than in L-T orientation and this may have contributed to the observed inclination. Reis et al. [30] tested three different structural steels in multi-axial fatigue. The materials have different early crack orientations. Findley's critical plane criterion [30] and other shear based multiaxial fatigue models gave good agreement with one of the materials, but not for the other two. This was attributed to differences in cyclic hardening. It is well possible that differences in anisotropy due to different textures between the different materials also play a role.

5 Conclusions

Material test results performed on 5 samples taken from rolled steel plates of existing structures aged between 25 to 50 years are presented. The steel grades were Fe510D or St52.3N, which are currently designated as S355J2 or S355N. The influence of the anisotropy of the microstructure of these deck plates was determined on the tensile strength, Charpy impact energy, and fatigue crack growth rate for crack plane orientations L-T, T-L and T-S.

The following conclusions are drawn:

- The anisotropy in material structure had a small or negligible influence on the yield stress and tensile strength. The anisotropy ratio for the elongation at fracture in T-L orientation, however, was lower than unity with a mean value of 0.86.
- Substantial influence of texture anisotropy was observed for the Charpy-V impact test results. The T-L and T-S anisotropy ratios were approximately 0.4. The upper shelf Charpy-V impact values were negatively correlated with the sulphur content in all tested orientations, but the anisotropy ratio was not correlated to the sulphur content. A negative correlation was observed between the anisotropy ratio and the Charpy-V impact value in L-T orientation.
- Standards do not require a minimum Charpy-V value in orientations other than L-T. A minimum value is optional for some steel grades. However, the relatively low upper shelf

Charpy-V values in transverse direction indicate that this may be critical in practical structures.

- The crack growth rate in T-L orientation was approximately 20 % higher as compared to the L-T orientation. Using Ellyin's low cycle fatigue crack propagation model, this difference in crack growth rate can be explained through the difference in strain at fracture between orientations T-L and L-T. This apparent anisotropy influence contributes to the variation in crack growth rates as observed in multiaxial fatigue tests.
- The crack growth rate in T-S orientation was substantially lower and more scattered than the rates in L-T and T-L orientations, with an anisotropy of 0.42. The remarkably low crack growth rate is attributed to the layered microstructure with a strong anisotropic nature. The layers act as temporary crack arrestors. This also explains the large scatter. The anisotropy in crack growth rate is not correlated to the anisotropy in upper shelf Charpy-V impact energy.

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References

- [1] Thompson SW, Howell PR. Factors influencing ferrite/pearlite banding and origin of large pearlite nodules in a hypoeutectoid plate steel. *Materials Science and Technology* 1992;8-9: 777-784.
- [2] ASTM E 399-08, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials, 2008.
- [3] King R. A review of fatigue crack growth rates in air and seawater. HSE Report OTH 511, Health & Safety Executive Books, 1998.
- [4] BS 7910:2013+a1:2015, Guide to methods for assessing the acceptability of flaws in metallic structures. BSI, London, 2015.
- [5] Kainuma S, Yanga M, Jeong Y-S. Experimental investigation for structural parameter effects on fatigue behavior of rib-to-deck welded joints in orthotropic steel decks. *Eng Fail Anal* 2017;79: 520–537.
- [6] Maljaars J, Bonet E, Pijpers RJM. Fatigue resistance of the deck plate in steel orthotropic deck structures. *Eng Fract Mech* 2018;201: 214–228.
- [7] Imam B, Salter PA. Historical load effects on fatigue of metallic railway bridges. *Proceedings of the Institution of Civil Engineers: Bridge Engineering*. 2018;171: 49-62.

- [8] Heiser F, Hertzberg R. Anisotropy of Fatigue Crack Propagation. *J of Basic Eng* 1971;June: 211-217.
- [9] Ohji K, Ogura K, Harada S, Taji T. Fatigue Crack Growth Behavior of Anisotropic Rolled Steel Plate with Special Reference to Laminated Structure and Inclusions. *Bulletin of JSME* 1978;21/156 : 939-947.
- [10] DIN 17100:1966-09, Allgemeine Baustähle - Gütevorschriften (in german), 1966.
- [11] EN 10025-2:2004, Hot rolled products of structural steels - Part 2: Technical delivery conditions for non-alloy structural steels, 2004.
- [12] ISO 643:2013, Steels - Micrographic determination of the apparent grain size.
- [13] TWI, Relating Charpy values from sub-size to full-size specimens. www.twi-global.com/technical-knowledge, 2019.
- [14] ISO 12108:2018, Metallic materials - Fatigue testing - Fatigue crack growth method.
- [15] EN 10025-3:2004, Hot rolled products of structural steels - Part 3: Technical delivery conditions for normalized/normalized rolled weldable fine grain structural steels.
- [16] Wilson A. Fracture mechanics properties of carbon and alloy steels. In: ASM Handbook vol. 19, 1998.
- [17] Ghosh A, Modak P, Dutta R, Chakrabarti D. Effect of MnS inclusion and crystallographic texture on anisotropy in Charpy impact toughness of low carbon ferritic steel. *Materials Science and Engineering A* 2016;654: 298-308.
- [18] Tada H, Paris PC, Irwin GR. The stress analysis of cracks handbook, 2nd ed. St Louis: Paris Productions Inc.; 1973.
- [19] Stephens MA. EDF Statistics for Goodness of Fit and Some Comparisons. *Journal of the American Statistical Association* 1974;69: 730–737.
- [20] Baptista CAP. Multiaxial and variable amplitude fatigue in steel bridges, Dissertation no. 7044 EPFL, Switzerland, 2016.
- [21] Huther M, Galtier A, Parmentier G, Marquis G. Guidance for the application of the best practice guide on statistical analysis of fatigue, IIW Doc. XIII-WG1-149-11, 2011, 1–27.
- [22] Schneider CRA, Maddox SJ, Best practice guide on statistical analysis of fatigue data, The Welding Institute doc. 13604.01/02/1157.02, 2002.
- [23] Kotrechko S, Stetsenko N, Shevchenko S. Effect of texture smearing on the anisotropy of cleavage-stress of metals and alloys. *Theoretical Applied Fract. Mech.* 2004;42: 89-98.
- [24] Baczynski GJ, Jonas JJ, Collins LE, **The influence of rolling practice on notch toughness and texture development in high-strength line pipe.** *Metall. Mater. Trans. A* 1999;30: 3045-3054.
- [25] Ellyin F. Fatigue damage - Crack growth and life prediction, Chapman & Hall, 1997.
- [26] Draper J. Modern metal fatigue analysis. EMAS publishing, 2007.

- [27] Dieter GE. Mechanical Metallurgy. 3rd Revised Ed, McGraw-Hill, 1989.
- [28] Walters CL, Alvaro A, Maljaars J. The effect of low temperatures on the fatigue crack growth of S460 structural steel. *International Journal of Fatigue* 2016;82: 110-118.
- [29] Murakami Y, Takahashi K, Toyama K. Mechanism of crack path morphology and branching from small fatigue cracks under mixed loading. *Fatigue Fract Eng Mater Struct*. 2005;28: 49-60.
- [30] Reis L, Li B, de Freitas M. Crack initiation and growth path under multiaxial fatigue loading in structural steels. *International Journal of Fatigue* 2009;31: 1660–1668.
- [31] Findley WN. A theory for the effect of mean stress on fatigue of metals under combined torsion and axial load or bending. *J Eng Ind* 1959:301–306.