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Material Effects on Risk Assessment of Residual Life of Oil Drilling Rig Pipe

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Abstract

Fracture mechanics parameters are used for numerical and analytical risk assessment of residual life of a cracked oil drilling rig welded pipe. Number of cycles to the critical crack length, obtained by direct integration of Paris law, verified by using extended Finite Element Method, are related to the number of cycles needed for 10 years of exploitation, to assess probability and risk due to fatigue crack growth.

Keywords: Risk Assessment, Residual Life, Fracture Mechanics Parameters, Oil Drilling Rig Pipe

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1. Introduction

New concept has been introduced recently for risk assessment of pressure vessels, based on structural integrity and life analysis, [1-7]. This concept goes well with activities of ESIS TC12, [8]. Consequences of a failure of pressure vessels can be extremely serious, even catastrophic, as explained in [3], but its frequency, i.e. probability of a failure is very low and typically related to welded joints, [4]. Detailed analysis of welded joints is given in [9, 10], while consequences of failure are analysed in [1-7]. In any case, risk, taken as the product of consequence and probability, can be significant. In the case of cracked oil drilling rig welded pipe consequence can be taken as medium, leaving risk to be “proportional” to probability.

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Probability determined by fracture mechanics parameters is introduced and explained in [1-7], based on “Expert opinion used in a systematic and structured process, [11]. In the case of a fatigue probability is defined as the ratio between the number of cycles for the given crack length and number of cycles for the critical crack length, [6, 7]. Reasoning behind is simple and based on the fact that probability of failure is proportional to defect size.

Having in mind simplicity, as one of the main features of risk based approach, analytical methods are preferable, like direct integration of Paris law, [6, 7, 12, 13], but their applicability is limited to simple geometries and should be checked/proved by more advanced and precise methods, capable of handling more complex geometries, like the extended Finite Element Method (xFEM), [6, 7, 14-21].

2. Experimental analysis of welded pipe

The High Frequency (HF) welded pipe with an axial crack, 2c=200 mm long and a=3.5 mm deep, Fig. 1, made of API J55 steel, was tested under pressure, as explained in [12, 13], and analysed here in respect to material effects, i.e. depending on crack position (weld metal – WM, heat-affected-zone – HAZ or base metal – BM), as well as on its state (old – exploited for 8 years, or new one).

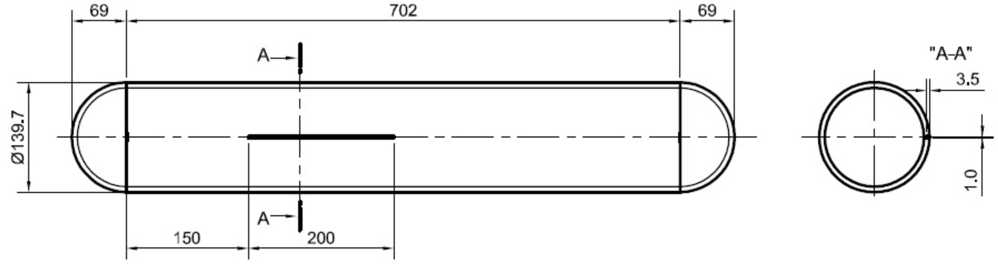


Figure 1. Oil rig testing pipe with an axial crack, [12, 13]

Basic operating data was: maximum pressure 10 MPa, minimum pressure 7.9 MPa, number of strokes of pump rod, n_{PR}=9.6 min^{-1}. Pipe diameter was 139.7 mm, thickness 7 mm.

Fracture toughness was estimated for all welded joint zones (BM, HAZ and WM) by using J_{Ic} values, as given in tab. 1 for both, old and new material. Critical crack lengths are given in the same way in Tab. 1, for two cases, one for edge crack with a/W=0.5, $Y(a/W)$=2.8, $K_{Ic}=2.8\cdot 100\sqrt{\pi a_c}$, the other one for central crack with $2c$=200 mm (Y=1), $K_{Ic}=100\sqrt{\pi c_c}$.

Table 1. Values for K_{Ic}, a_c and $2c_c$ for old / new material

	J_{Ic} [kN/m]	K_{Ic} [MPa m$^{1/2}$]	a_c [mm]	$2c_c$ [mm]
BM	35.8 / 63.1	91.4 / 121.4	33.9 / 59.8	532 / 938
HAZ	48.5 / 68.4	106.4 / 126.4	46.0 / 64.9	721 / 1017
WM	45.7 / 64.1	103.3 / 122.3	43.3 /60.8	680 / 953

Paris law coefficients C and m obtained by testing fatigue crack growth (FCG) in new and exploited material, in both cases for BM as the most crack sensitive zone, [6, 7, 12, 13], are presented in Table 2 and Fig. 2, and explained in more details in [12, 13].

Table 2. Results for fatigue testing of old and new material (BM)

	ΔK_{th} [MPa√m]	C [m/ciklusu·MPa√m]	m [-]	da/dN [m/cyc] for ΔK=15 MPa√m
New material	9,5	$1{,}23 \cdot 10^{-13}$	3,931	$5{,}17 \cdot 10^{-9}$
Old material	9,2	$2{,}11 \cdot 10^{-15}$	6,166	$3{,}75 \cdot 10^{-8}$

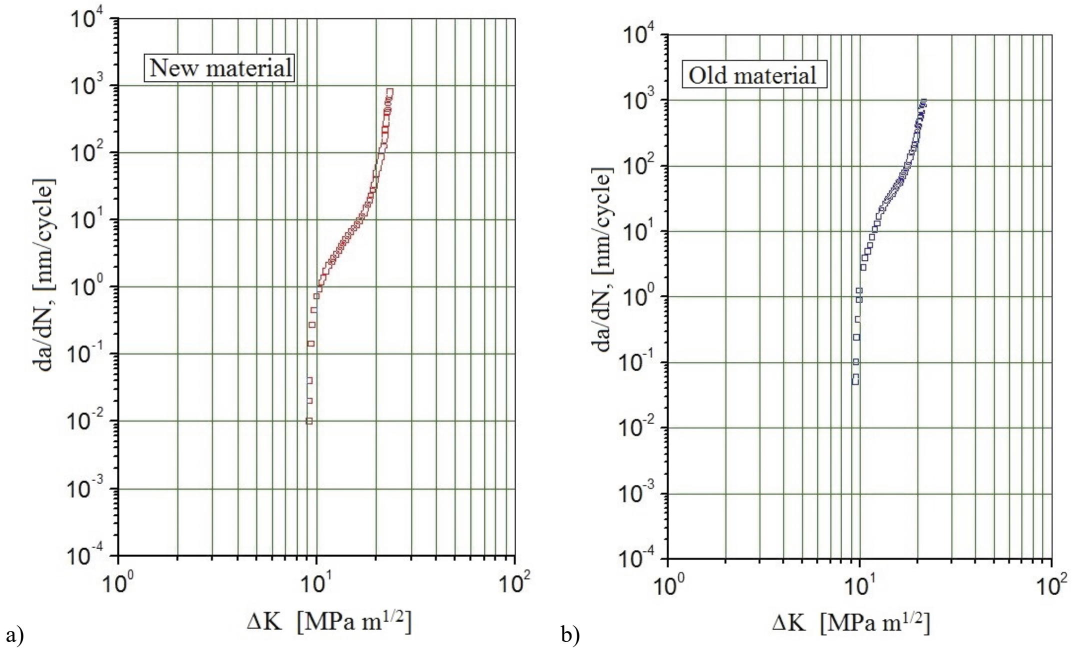


Figure 2. FCG vs. ΔK for (a) new material, ΔK_{th}=9.2 MPa√m: (b) old material, ΔK_{th}=9.5 MPa√m

Having these values in mind, number of cycles for crack growth will be evaluated for both new and old materials, into depth from a=3.5 mm up to 7 mm (since all critical crack depths are larger than the thickness), and then into length from $2c$=200 mm up to the values given in Table 2 for different welded joint zones. This means that different Paris law coefficients of welded joints zones affect crack growth both into depth and length, but fracture toughness affects only growth into depth.

3. Remaining life estimation

To calculate remaining life, Paris law is used:

$\frac{da}{dN} = C(\Delta K)^m = C\left(Y(\frac{a}{W})\Delta\sigma\sqrt{\pi\cdot a}\right)^m$ where $Y(a/W)$ is the geometry factor depending on crack length and geometry (component width), ΔK stress intensity factor range corresponding to stress amplitude $\Delta\sigma$=21.2 MPa. It was shown, [7], that the fatigue crack growth was first into depth, and then along pipe length.

3.1 Crack growth into depth/through pipe thickness

For the first phase of crack growth, i.e. its growth into depth, the initial length (depth) was 3.5 mm, with the final length 7 mm, to be used in directly integrated value of number of cycles:

$$N = \frac{2}{(m-2)\cdot C\cdot(Y(a/W)\cdot\Delta\sigma)^m\cdot\pi^{\frac{m}{2}}}\left(\frac{1}{a_0^{\frac{m-2}{2}}} - \frac{1}{a_{cr}^{\frac{m-2}{2}}}\right)$$

Geometry coefficient Y(a/W) was taken as constant and equal 2.5 for an edge crack with a/w=0.5, resulting in the number of cycles 26,469,221 for old material, C=2.11E-15, m=6.166.

The extended FEM (xFEM) was then applied to evaluate the number of cycles under fatigue loading and to check the accuracy of direct integration of Paris law. This method is relatively new, and successfully applied to solve different problems [6, 7, 14-21]. As described in [6], two FE models were used, one with course mesh (129,989 nodes) and the other with fine mesh (414,537 nodes), proving sensitivity of xFEM results on mesh refinement, [22]. As the relevant result, 15,968,030 cycles was accepted, obtained with the refined mesh. Results for the stress intensity factor distribution is shown in Fig. 3 for four different crack lengths (depths).

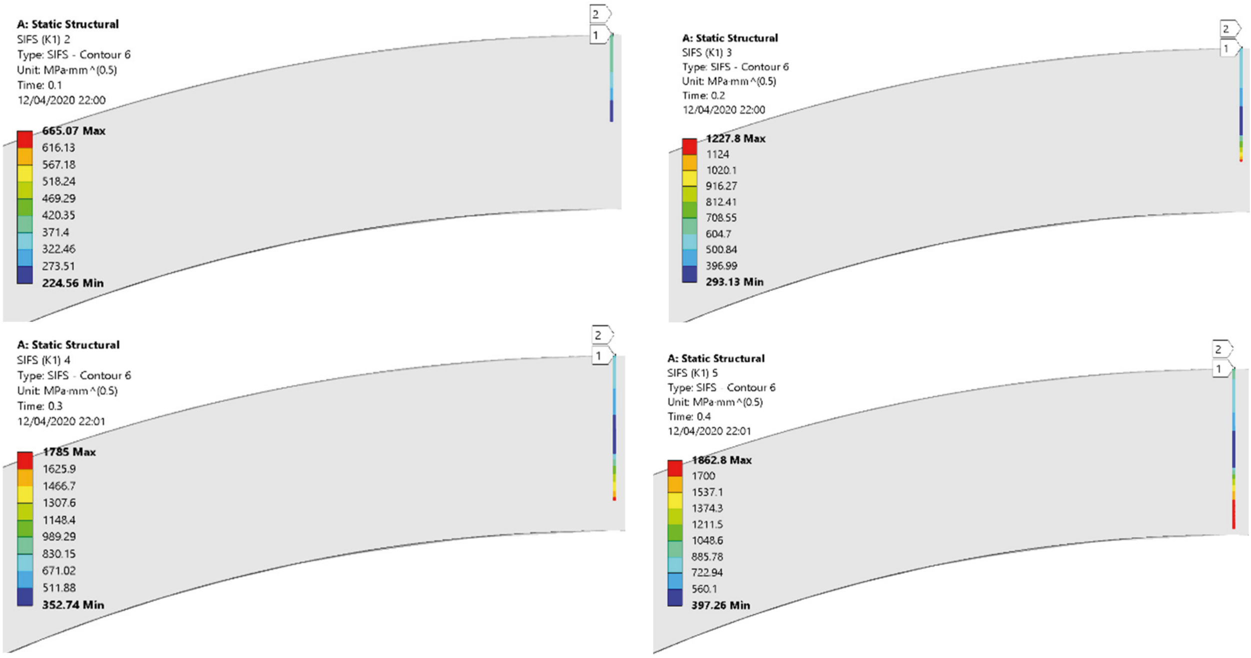


Figure 3. Results for SIF for crack length 3.5 mm (top left) 4.83 mm (top right), 5.83 mm (bottom left), 6.86 mm (bottom right)

Comparing this the result obtained directly by applying Paris law one can see that the agreement with refined mesh is good, but one should notice that the constant *Y(a/W)=2.5* was used in direct integration of Paris law, which provides significantly longer life than real. Therefore, further calculations with *Y(a/W)* values corrected for different crack length (depth) values was needed, i.e. direct integration of Paris law was still used, but for small crack growth steps (0.7 mm) to accommodate different *Y(a/W)* values. In this case, only the first growth interval (from 3.5 to 4.2 mm) provides number of cycles which is worth calculating, being 6,373,604, since already the next one (from 4.2 to 4.9 mm) has only 29,321 cycles, while the later ones are negligible due to significant (exponential) increase in *Y(a/W)* values. Therefore, the remaining life evaluated by direct integration of Paris law would be 6,402,925, i.e. significantly smaller than the corresponding xFEM value. This is in accordance with explanation given in [6, 7], and results given in [7], where similar comparison was made for crack growth from 1 mm to 1.42 mm, table 3. One should notice that by using a relatively short crack length, the effect of *Y(a/W)* was practically avoid. One should also notice that *Y(a/W)* was taken as constant and equal to 1.12, which is not completely correct since its final value (for a=1.42) is 1.45, but this effect is not significant and would actually further reduce number of cycles with increasing crack length, to level up the ratio between two estimations, table 3, bottom raw. In any case, number of cycles obtained by direct integration of Paris law is a conservative estimation, because it was calculated for 2D problem with an edge, through crack, whereas number of cycles obtained by xFEM was calculated for a real, 3D surface crack.

Table 3. Number of cycles (given in 10^9) for xFEM and directly integrated Paris law

Crack lengh (depth), a (mm)	1.14	1.22	1.28	1.35	1.42
xFEM from ref. [6]	1.07	1.39	1.57	1.67	1.73
Direct integration from ref. [6]	0.41	0.60	0.73	0.87	0.99
Direct.integration, corrected here	0.40	0.52	0.62	0.71	0.78

Now, once the direct integration of Paris law has been verified and "quantified", one can proceed with calculation of number of cycles for new material in the first phase of crack growth (through the thickness) and then for new and old material in the second phase of crack growth, including different welded zones due to different critical crack lengths, as given in table 1. In the case of crack growth through new pipe thickness, one gets 5,618,590 cycles, which is somewhat surprising, since longer life was expected. The explanation is that Paris coefficients have been evaluated according to the experimental procedure prescribed by ASTM E647, as described in [12, 13, 23], for *ΔK*=15 MPa√m range starting with

9.2 MPa√m (old material) or 9.5 MPa√m (new material), Fig. 2. In this ΔK range, e.g. ΔK=15 MPa√m, crack growth rate is higher for the old material, table 2, as expected. Anyhow, in our case, $\Delta K=2.5\cdot 21.2\sqrt{\pi}\cdot 0.035=5.56$ MPa√m, is significantly smaller, which in combination with Paris law coefficients (C larger for new material, m smaller, making the effect of the first one dominant for smaller ΔK, thus producing unexpected total effect) explains this issue and opens the question about limitations of the procedure for C and m evaluation.

Finally, one should also keep in mind that number of cycles for a crack to penetrate through the thickness in one year of operation can be calculated as follows: $Ny=60\cdot Ty\cdot n= 60\cdot 8760\cdot 9.6 = 5.046\cdot 10^6$ cycles, where Ty is number of working hours per year.

3.2. Crack growth along pipe length

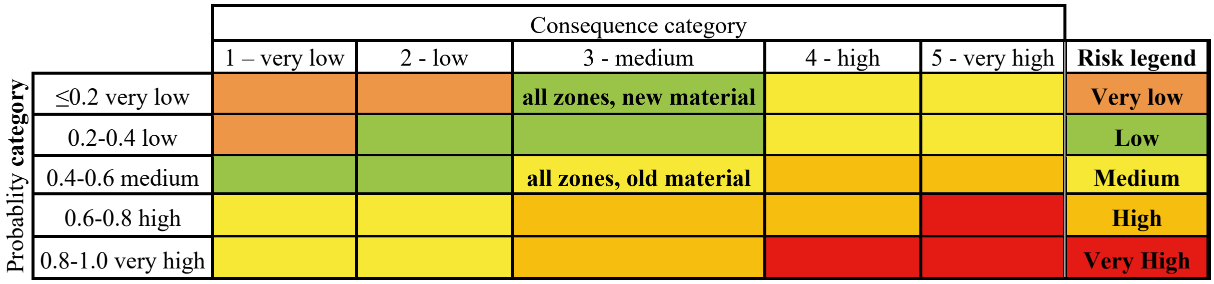
Results are presented in table 4 (number of cycles for crack growth into length, N_{length}, as well as the total number of cycles, N_{total}, calculated as the sum of number of cycles for crack growth into depth and length) and can be used to evaluate the effects of material properties, both its state and welded joint zones. It is obvious that the effect of material state is significant, whereas the effect of material heterogeneity (expressed only through different fracture toughness, i.e. critical crack length, and not through FCG rate, since there were no data for WM and HAZ for C and m, so data for BM was used for all three welded joint zones) is negligible. One should notice that in the case of crack growth along pipe length value of amplitude SIF is significantly higher, ΔK=16.8 MPa√m, than in the case of crack growth through thickness, explaining why new material has now much longer life, as expected. Table 4 shows also remaining life (N_{total}/N_y), as well as probabilities of failure calculated as the inverse of remaining life.

Table 4.

	$2c_c$ [mm] old / new	N_{length} (cycles) old / new	N_{total} (cycles) old / new	Remaining life (N_{total}/Ny)	$Probability_{total}$ old / new
BM	532 / 938	4,668,449 / 38,874,144	11,070,744 / 44,492,734	2.19 / 8.82	0.46 / 0.11
HAZ	721 / 1017	4,995,518 / 39,713,340	11,397,813 / 45,331,930	2.26 / 8.98	0.44 / 0.11
WM	680 / 953	4,948,430 / 39,034,334	11,350,725 / 44,652,924	2.25 / 8.85	0.44 / 0.11

4. Risk assessment

Table 5 presents the risk matrix for fatigue failure of an oil drilling rig pipe, with consequence taken as the medium, [6, 7], and probabilities as given in Table 4. One should notice medium risk of failure for old material, contrary to very low risk for new material, as well as no effect of welded joint zones on risk assessment, which is partly due to the fact that no data was available for Paris law for HAZ and WM. Anyhow, this is conservative estimation, since one can expect slower fatigue crack growth in HAZ and WM, compared with BM in the case analysed here.



		Consequence category					
		1 – very low	2 - low	3 - medium	4 - high	5 - very high	**Risk legend**
Probability category	≤0.2 very low	🟧	🟧	🟩 **all zones, new material**	🟨	🟨	🟧 **Very low**
	0.2-0.4 low	🟧	🟩	🟩	🟨	🟨	🟩 **Low**
	0.4-0.6 medium	🟩	🟩	🟨 **all zones, old material**	🟠	🟠	🟨 **Medium**
	0.6-0.8 high	🟨	🟨	🟠	🟠	🟥	🟠 **High**
	0.8-1.0 very high	🟨	🟨	🟠	🟥	🟥	🟥 **Very High**

5. Conclusions

Based on presented concept and results, one can conclude the following:

- Direct integration of Paris law provides conservative estimate of residual life and probability of failure since it can handle only simple geometry. For more precise analysis of complex geometries, FEM and xFEM should be used. Another problem is the effect of geometry factor Y(a/W), since it might need small steps in direct integration process to accommodate significant changes in its value during crack growth and change of its length.

- Material effects on remaining life and probability of failure are significant in respect to its state (old vs. new), but negligible in respect to welded joint heterogeneity.
- Risk based analysis is useful method for managers to decide on further use of a cracked component.

6. Literature

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