Bending Effects on Fatigue Crack Propagation of Circumferential Butt Welds of API 5L X-65 Steel

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Abstract. *The results of a study of bending effects on fatigue crack propagation in circumferential welded joints of API grade X-65 pipeline steel are presented. These pipes can be used as rigid risers in submarine oil and gas elevation from the seabed of the ocean to the surface of deep seas. The welded joint regions studied were the base metal, heat affected zone and weld metal. The crack growth curves were obtained under constant stress range conditions at the stress ratio levels of 0.1 and 0.5. Fatigue tests were done with specimens subjected to previous plastic deformation by bending followed by deflection to straighten them, to reverse deformation levels of 3%. This procedure simulates the behaviour of the riser when it is bended and then straightened for Reel-lay installation in the sea. The specimens were obtained from pipes of 600 mm diameter and 14.5 mm wall thickness. The test procedures followed the ASTM standards. The results obtained show that the different welded joint regions showed different da/dN x DK curves and the influence of the stress ratio on those curves. It can also be concluded from the results that the crack propagation rate appears to be affected by the flexure/deflexure procedure and welded joint defects.*

Keywords. *Fatigue, Crack Propagation, Welded Joints, Rigid Risers, Pipeline Steel.*

1. Introduction - *RISERS*

Rigid risers are critical components of deep sea production oil systems. They are the link between the manifold on the seabed and the platform on the surface, through where the oil flows. When this link occurs between fixed and floating points (platforms or vessels) dangerous loads due to the relative movement appear and, in addition with the sea and sub sea streams flowing through the pipes, cause some variable loads produced by the vortex induced vibration (VIV). Others effects like the pressure inside and outside the pipes, the low temperature of the seabed, the aggressive environment, could cause damage and variable stresses that strongly affect the fatigue life of the riser.

Another important aspect is the fabrication and the dropping of the riser. They are done simultaneously using vessels specially designed for this purpose. The union of the tubes is done using circumferential butt welds which due to their internal dimensions only allow external welding (*one side welding*). After that operation an inspection (x-ray or ultrasound) is done, followed by the drop of the riser. All that is a complex and expensive operation (≈ US$ 70.000,00/day) with a launch rate of about 1000 m/day, according to Teixeira et al (1997) and Sanderson et al (1999). There are three ways to drop (lay on) a riser: *S-Lay*, *J-Lay* and *Reel-lay*.

The reel-lay method consists in to rolling up the riser around a 7 to 12 meters diameter wheel and after its transportation, unroll it directly to the sea. This process involves a plastic deformation due to the flexure and subsequent deflexure of the riser.

The work presented here is focused at this reverse bending and its influence on the fatigue crack propagation. The crack growth curves were obtained for the three regions of the weld joint, the base metal (BM), the weld metal (WM) and the heat affected zone (HAZ) at two stress ratios, R = 0.1 and 0.5. The results are compared with the curves without bending, obtained from de Marco and Bastian (2002) and de Marco (2002).

2. Materials and Methods

The material used in this research is an API 5L grade X-65 steel used for the fabrication of oil and gas pipelines and rigid risers. The specimens were cut from the circumferential weld as shown in figure 1.

Table 1 – Main characteristics of the welding procedure.

Electrode	**Welding Conditions (average values per pass)**
Manufacturer: LINCOLN Diameter [mm] = 1.0 Type of mixture: air/CO_2 – 50/50 Flow rate [l/min] = 55	Amperage [A] = 229 Voltage [V] = 24.7 Welding speed [cm/min] = 70 Heat input [kJ/cm] = 5.0

The weld process of the circumferential butt welds was the Gas Metal Arc Welding (GMAW) automatic. The main characteristics of the welding process are shown in table 1.

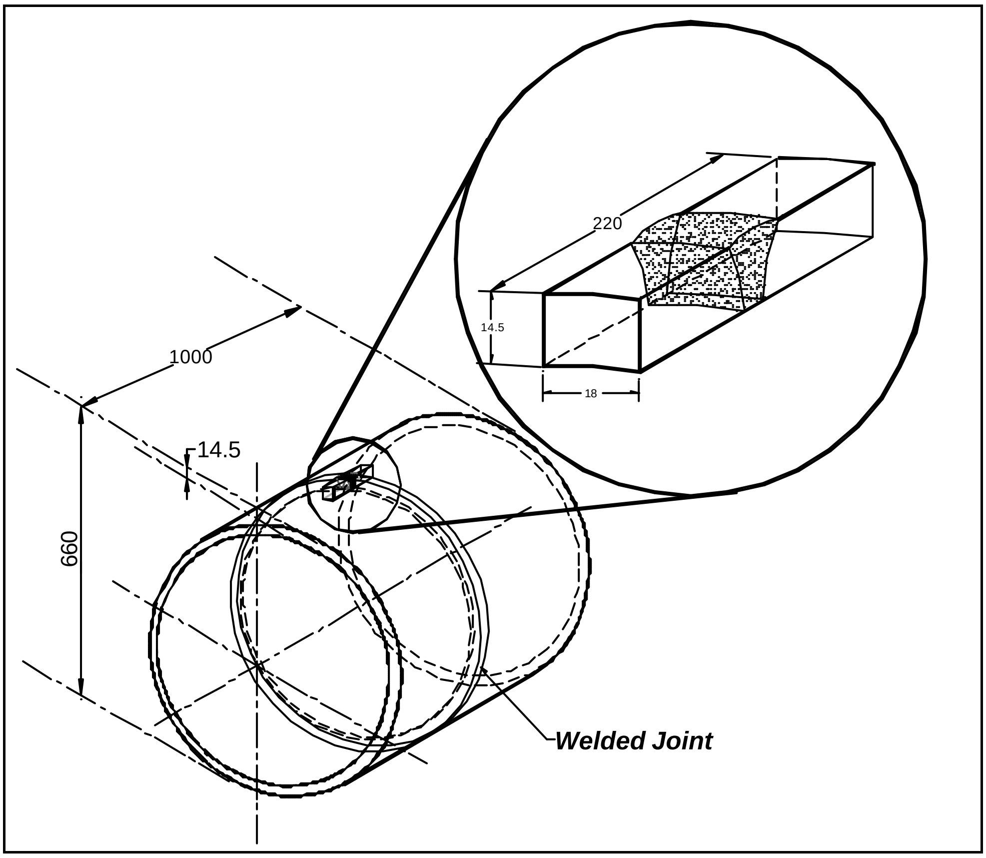


Figure 1 – Welded pipeline source of the specimens used.

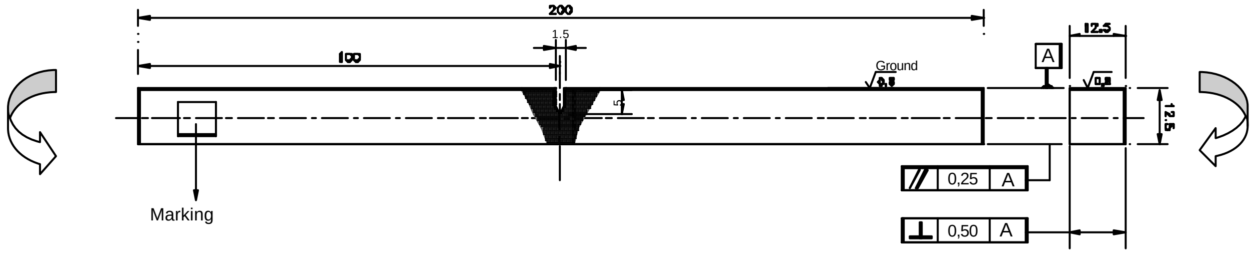
Although the dimensions of the specimens used were smaller than the ones recommended by the standard, they have some interesting advantages, as reproducing the thickness of the real pipes from which the specimen were cut. According to Maddox (1998), this gives the tests conditions closer to the real ones and a greater reliability for the results.

3. Experimental Procedures

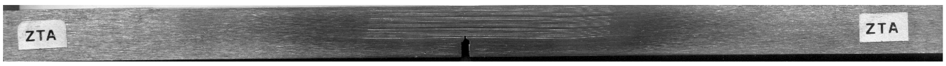
The simulation of the effects of the *riser* bending during its flexure and followed deflexure around the reel (wheel) in the regions of the butt weld were obtained by bending followed by a reversed bending (opposite direction) with a load equivalent to a deformation of 3% of the maximum load applied, before the machining the notches. That value (3%) was obtained from a stress x strain test previously done. The results are shown in table 2. After this, the notches were machined in the three welding regions and the fatigue crack propagation tests were carried out according to the standards procedures BS 6835 (1988), ASTM E 647 (1999) and API 579, ap. F (1979). Figure 2 shows the applied bending and reversed bending over the fatigue specimen (a) and the final configuration of the specimen with the notch and the horizontal marks etched for visual inspection (b).

Table 2 – Mechanical properties of the API 5L grade X-65 steel used.

Property	**Symbol**	**Value [MPa] (minimum)**	**Vickers hardness - HV**		
Yield strength	S_y	442	BM	HAZ	WM
Ultimate Tensile strength	$S_{máx}$	580	208	223	212
Young's modulus	E	207000			

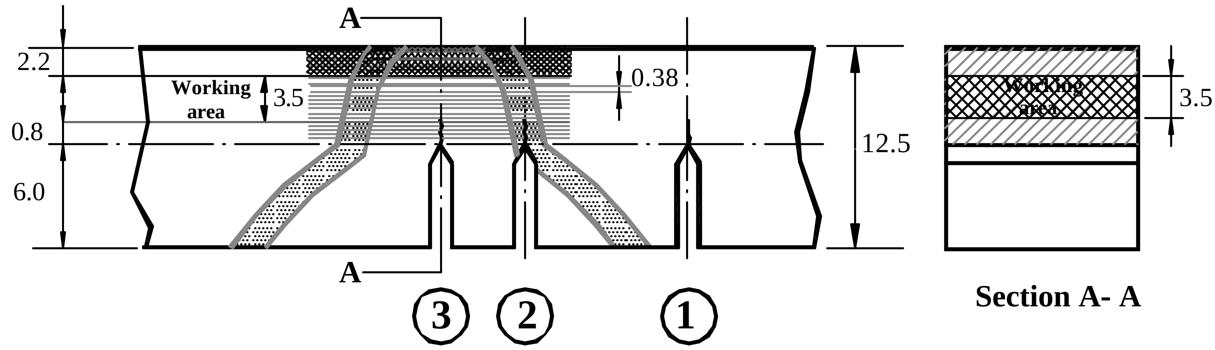


(a)



(b)

Figure 2 – Applied bending and reverse bending over the fatigue specimen (a) and the final configuration of the specimen (b).



① Base Metal (BM) ② Heat Affected Zone (HAZ) ③ Weld Metal (WM)

Figure 3 – Notches positions and dimensions of the specimen used for fatigue propagation tests.

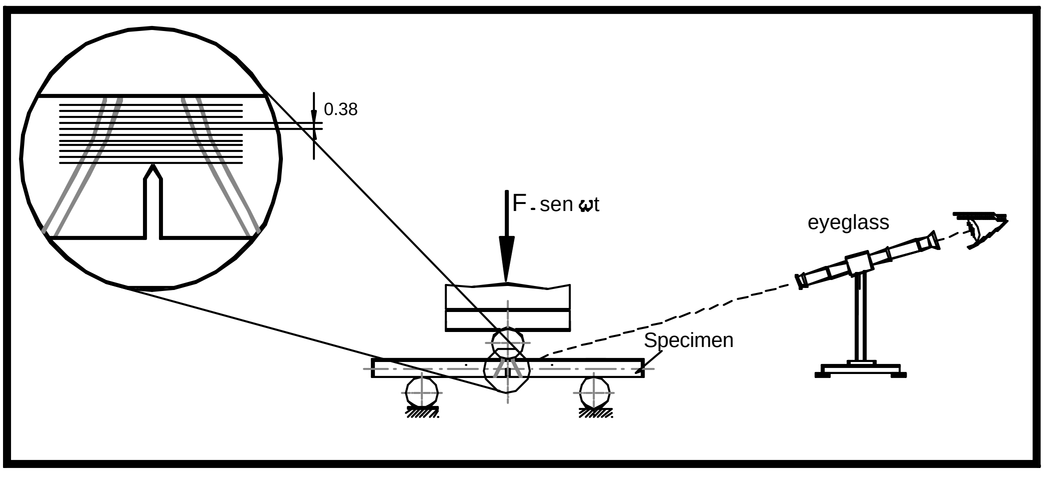
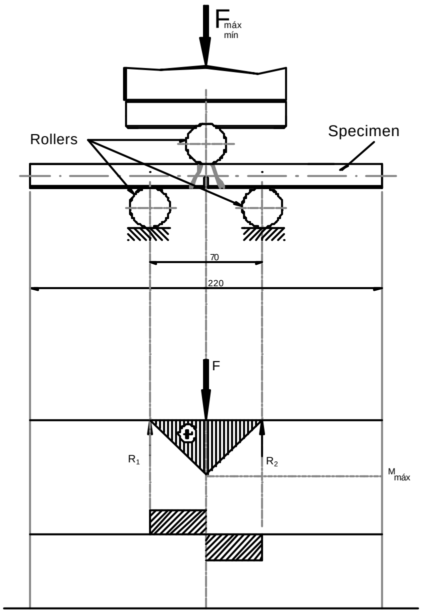


Figure 4 – Visual measurement system used.

The experimental procedure followed in the work was:

- Variable initial load for crack initiation, with ΔK value 50% greater than the used during the tests.
- When the crack was formed the applied load was gradually reduced, until the crack and ΔK reached a length and a value suitable for the tests,.
- Measurement of the increase in crack length (fig. 3), Δ*a*, the maximum and minimum loads, ΔF(*a*), and the correspondent number of cycles, N(*a*).

The suitable initial ΔK value was obtained from references BS 6835 (1988) and BS 5762 (1979), where a range of values for ΔK is recommended which guarantees that crack propagation will always occur in the linear elastic region.



The general conditions of the tests were:

- Senoidal load;
- Specimen: *Single Edge - Bending* - SE(B),
- Orientation L-R;
- Frequency = 30 Hz;
- R = 0.1 e 0.5;
- Initial crack - $a_i \approx 0.8$ mm;
- Initial $\Delta K_i \approx 12$ $MPa.m^{1/2}$;
- Mean temperature ≈ 20^o C;
- Ambient: air;
- Relative humidity of the air ≈ 60%.

Figure 5 – Three points fatigue propagation test.

The minimum crack length was adopted according to references ASTM E 647 (1999) and BS 5762 (1979).

4. Results and Discussion

The results of the tests of fatigue crack propagation are shown below. Figures 6 and 10 show the crack growth curves for the three regions of the welding joint and stress ratios, R = 0.1 and 0.5, respectively. Figures 7 to 9 and 11 to 13 show the crack growth rate for each region subjected to bending and de-bending of 3%, at the same stress ratio.

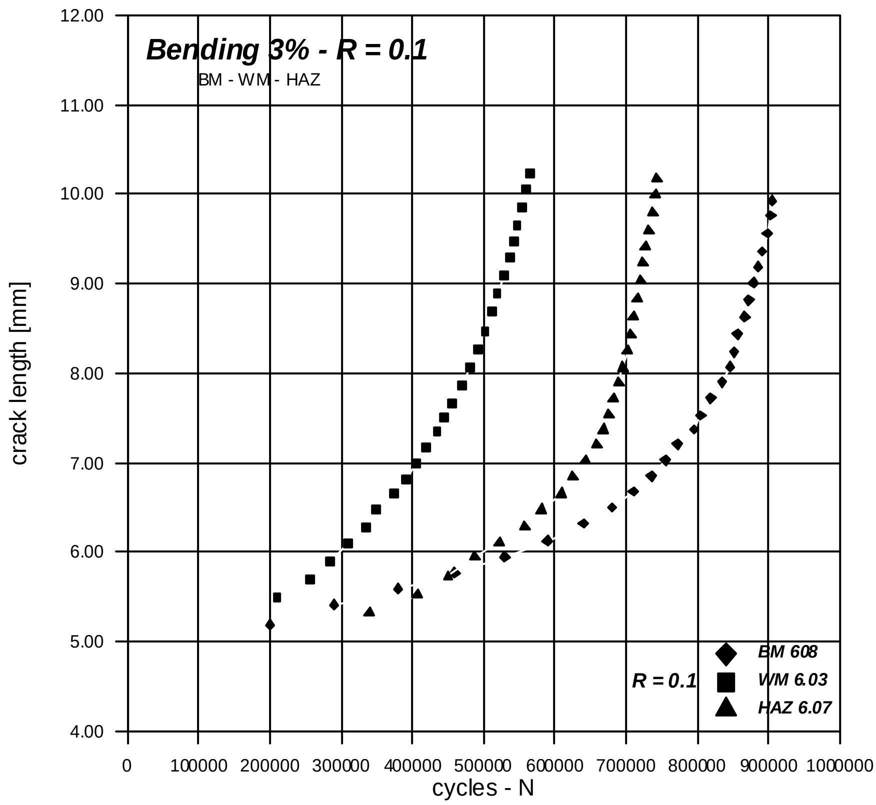


Figure 6 – a x N – BM-WM-HAZ – R = 0.1 – bending 3%.

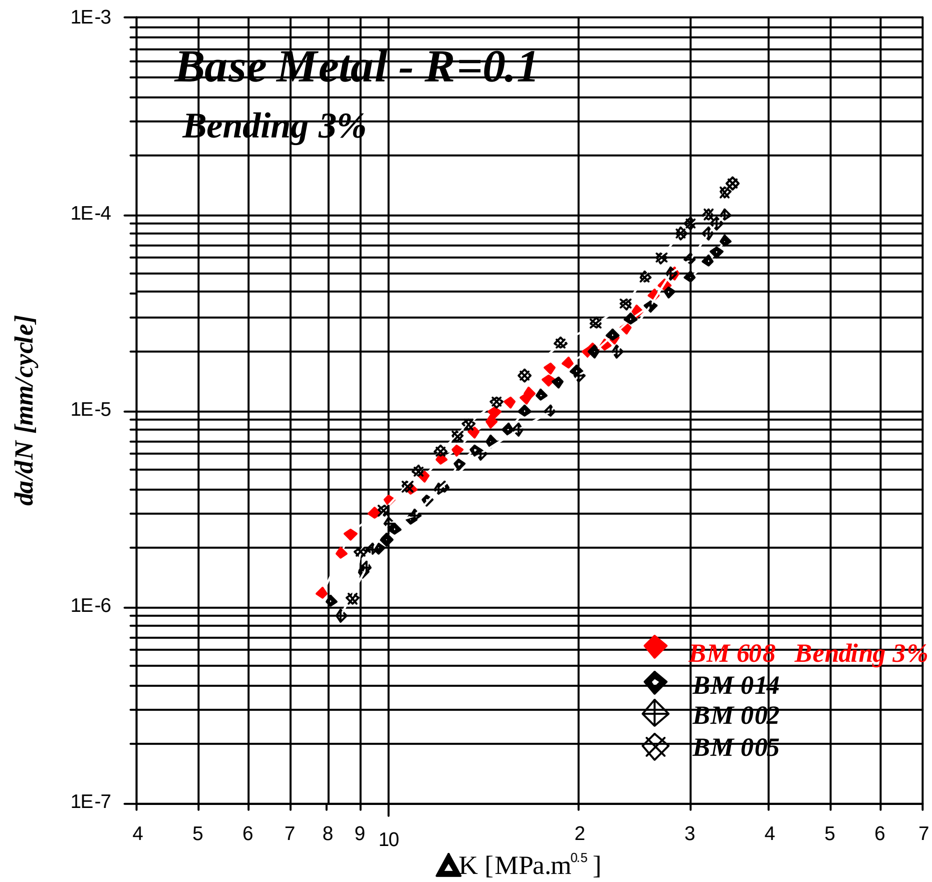


Figure 7 – d*a*/dN x ΔK – Base Metal – R = 0.1 – bending 3%.

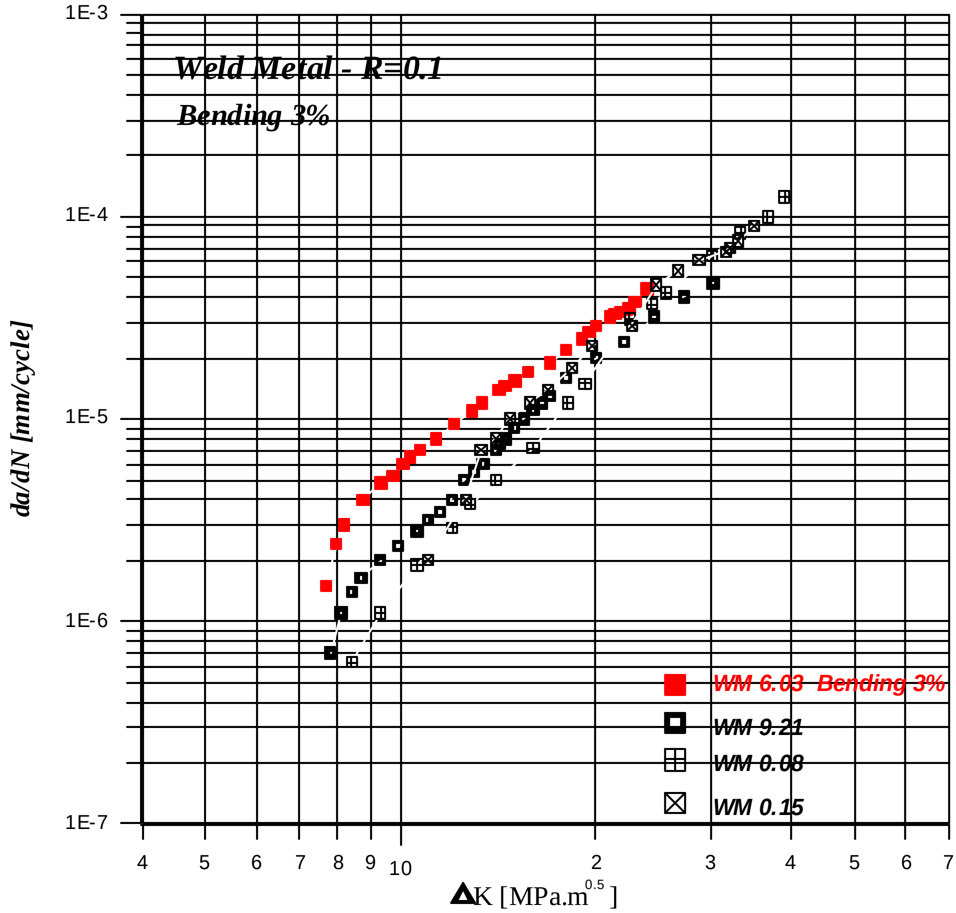


Figure 8 – d*a*/dN x ΔK – Weld Metal – R = 0.1 – bending 3%.

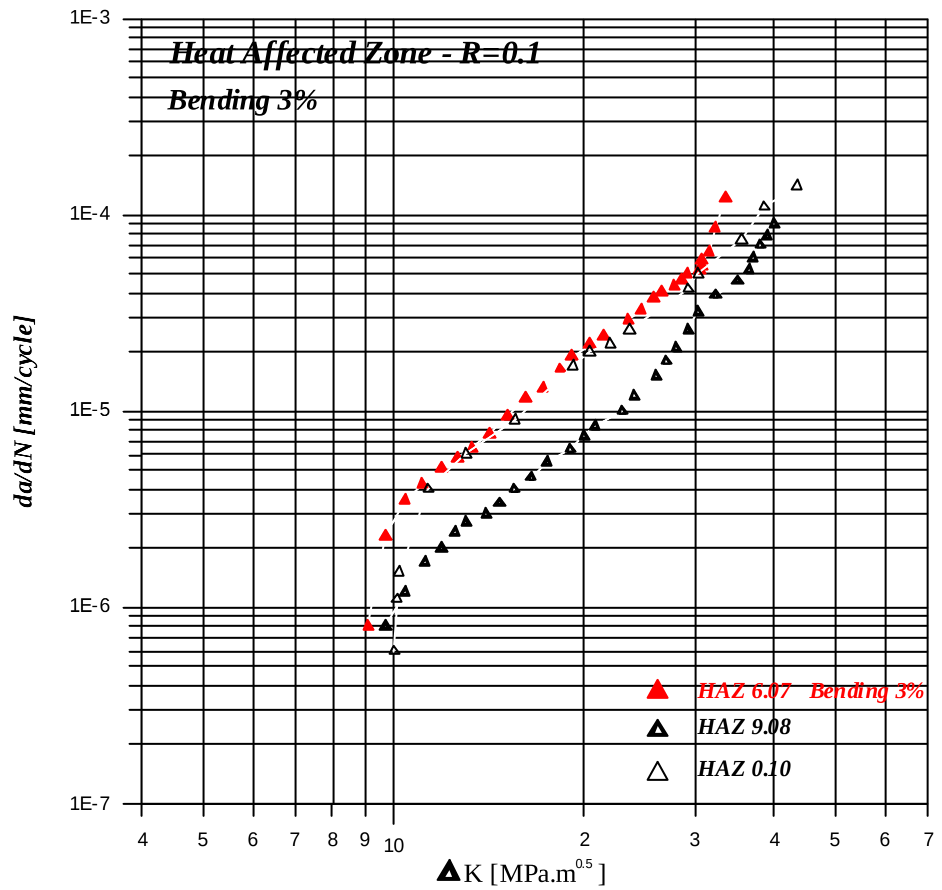


Figure 9 – d*a*/dN x ΔK – HAZ – R = 0.1 – bending 3%.

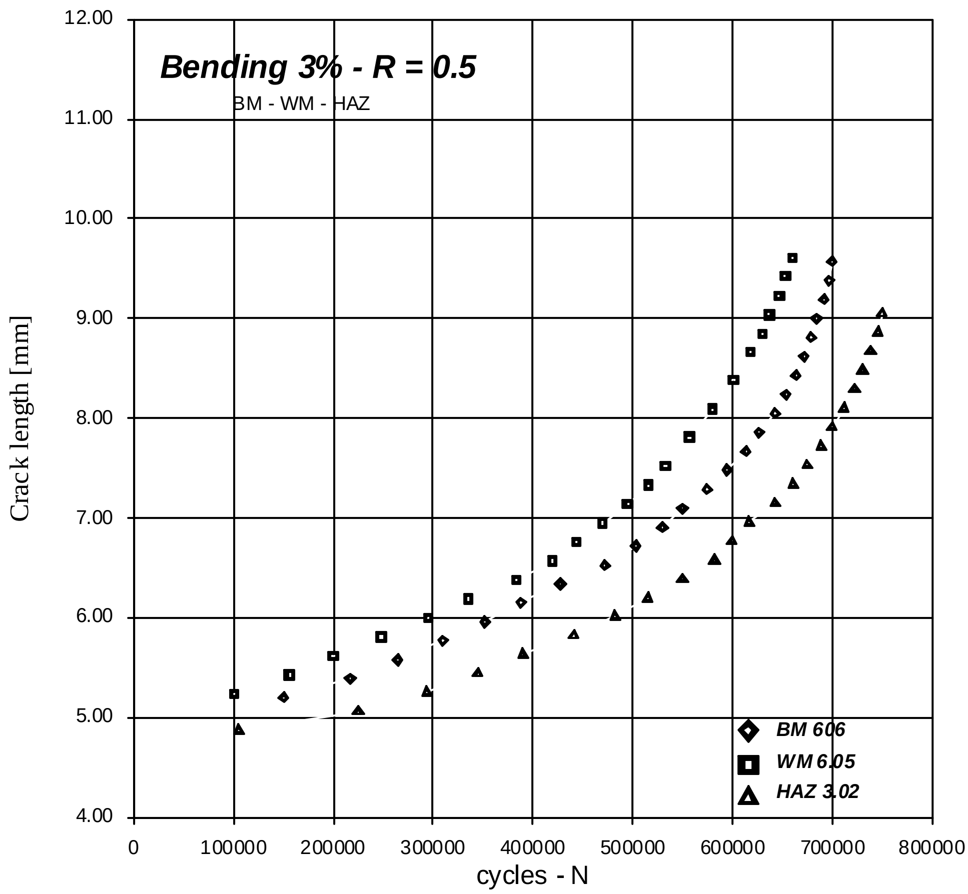


Figure 10 – *a* x N – BM-WM-HAZ – R = 0.5 – bending 3%.

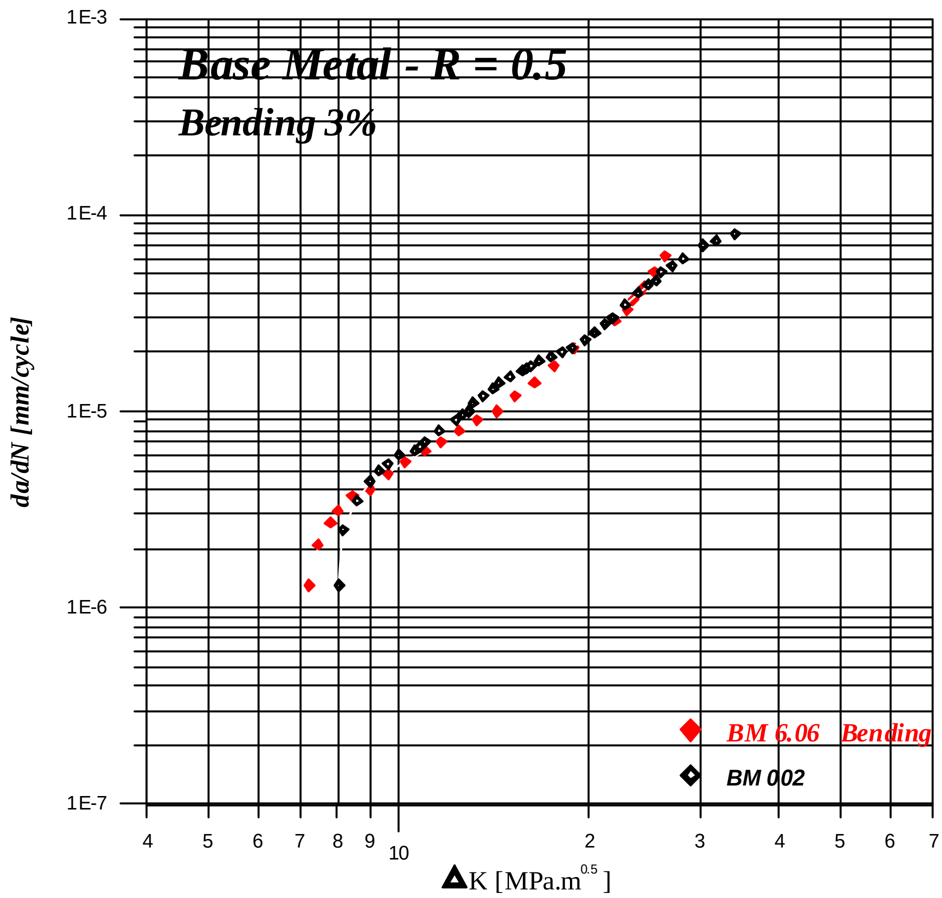


Figure 11 – d*a*/dN x ΔK – Base Metal – R = 0.5 – bending 3%.

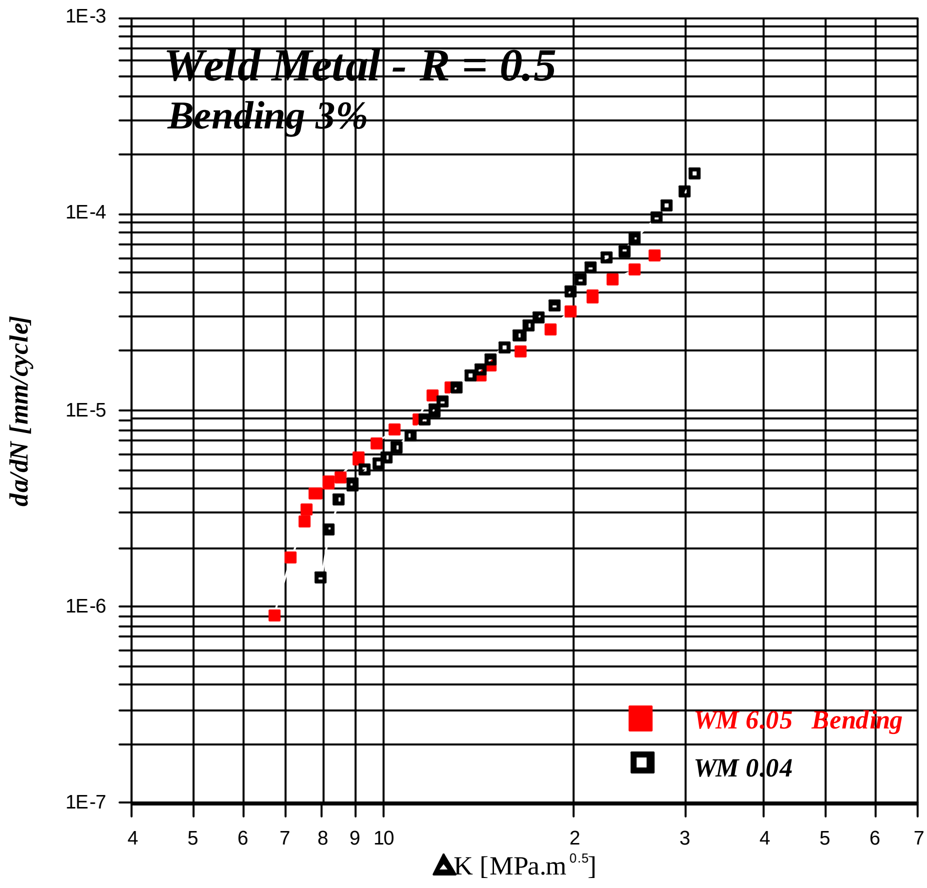


Figure 12 – d*a*/dN x ΔK – Weld Metal – R = 0.5 - bending 3%.

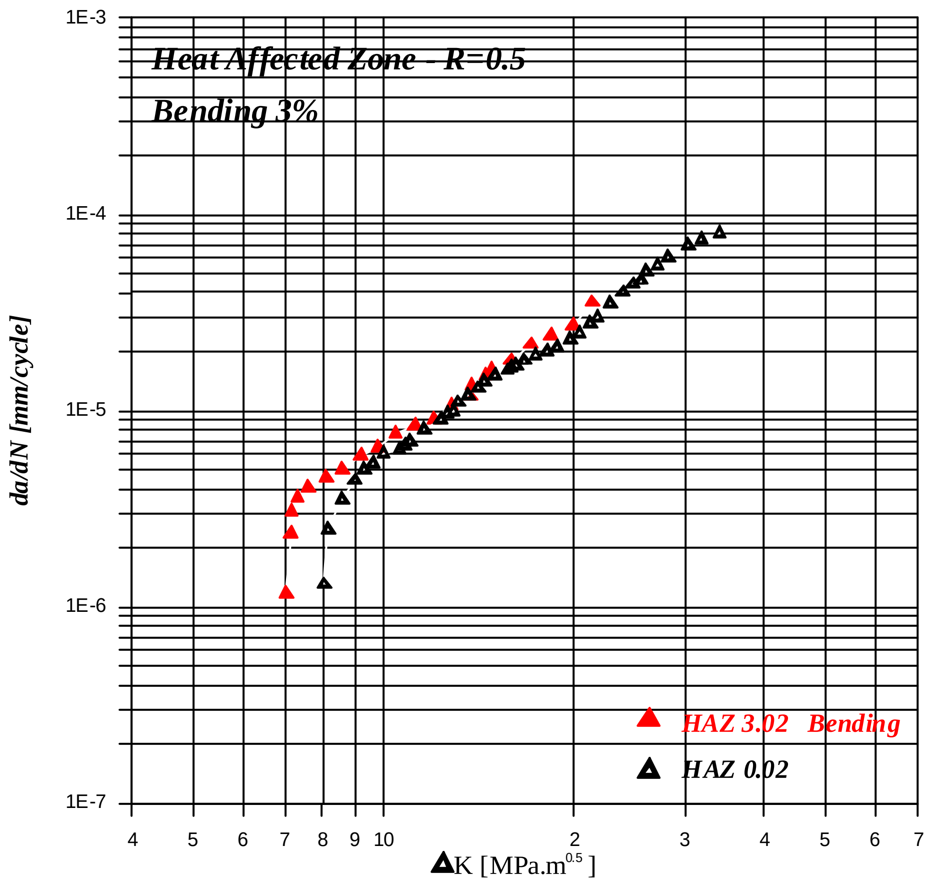


Figure 13 - d*a*/dN x ΔK – HAZ – R = 0.5 – bending 3%.

No effects of the flexure/deflexure process were observed on the base metal region, as shown in figure 7, where a comparison is done among three others specimens, according to the references de Marco and Bastian (2002) and de Marco (2002).

However, in figures 8 and 9, corresponding to the regions of the weld metal and heated affected zone, a small displacement to the left of the propagation curve can be noted, showing an acceleration of crack propagation rate comparing to the curves obtained from tests without bending. This shows that the flexure/deflexure process could have some influence on the fatigue crack propagation behaviour of the specimens.

No significative flexure/deflexure effects on the fatigue crack propagation behaviour were observed in the three regions of the weld for stress ratio R = 0.5, as shown in figures 11 to 13.

5. Conclusions

An examination of the results of the fatigue crack propagation tests on the three regions of the welded joints under the effect of bending followed by another bending with the same value, but in the opposite direction, to simulate the bending effects that the rigid *riser* is subjected when rolled up and farther unrolled for launching to the sea, leads to the following conclusions:

- With stress ratio 0.1, a small increase in the fatigue crack propagation rate in the weld metal and heat affected zone regions was detected, showing some influence of flexure/deflexure of 3% process on the fatigue behaviour of the welded joint.
- No effects on the fatigue behaviour were observed for stress ratio R = 0.5 in the three regions of the welded joint, as shown by figures 10 to 12.
- In all crack propagation tests carried out the crack started and grew in a region of the material previously cold worked (Hertzberg, 1976), caused by the previous flexure and deflexure of 3% of the specimen. This cold work process apparently has a small influence in the fatigue crack propagation behaviour of all different regions of the welded joint.

6. Acknowledgements

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7. References

TEIXEIRA, M. J. B., LONGO, C. E. V., SERTÃ, S. R. R., "Barracuda Field: Installation of 34 Flexible Risers in FPSO System", Offshore Technology Conference, Hudson, Texas, USA, 1997.

N. SANDERSON, T. MOROS, P. FAIRHARST, G. HARRISON, "Design and Practical Considerations of Steel Catenary Riser and Pipeline Systems", 2nd Workshop on Sub-sea Pipelines, Rio de Janeiro, RJ, Brasil, 1999.

DE MARCO, F. F. e BASTIAN, F. L – "Propagação de Trincas de Fadiga de Juntas Soldadas de *Risers* Rígidos Fabricados em Aço API 5L grau X-65" - Anais do CBECIMAT 2002, Natal, RN, 2002.

DE MARCO, F. F., "Propagação de Trincas de Fadiga em Juntas Soldadas Circunferenciais de Aço API 5L Grau X-65 para Utilização em Risers Rígidos", Tese de D.Sc., COPPE/UFRJ, Rio de Janeiro, RJ, Brasil, 2002.

MADDOX, S. J. "Fatigue Performance of Large Girth Welded Steel Tubes", Proceedings of 17th OMAE98, July 5-7, Lisbon, Portugal, ASME, 1998.

BS 6835 - Method for Determination of the Rate of Fatigue Crack Growth in Metallic Materials – 1988.

ASTM E 647 – Standard Test Method for Measurement of Fatigue Crack Growth Rates, Annual Book of ASTM Standards – Vol. 11.03, 1999.

API 579 – APPENDIX F – Material Properties for A Fitness for Service Assessment – January, 2000.

BS 5762 - Methods for Crack Opening Displacement (COD) Testing – 1979.

HERTZBERG, R.W., "Deformation and Fracture Mechanics of Engineering Materials", John Wiley & Sons Inc., NY, USA, 1976.

BRANCO, C. M., RANDOM, J. C. E CULVER, L. E., "Growth of Fatigue Cracks in Steels" – Metal Science, Vol. 10, nº. 5, pp 146-152, 1976.

MOURA BRANCO, C. *et al*., *Fadiga de Estruturas Soldadas*, Fundação C. Gulbenkian, 1987.

GURNEY, T. R. "Fatigue of Welded Structures", Cambridge University Press Cambridge, UK, 1968.

GURNEY, T.R., "Fatigue Design Rules for Welded Steel Joints", The Welding Institute Research Bulletin, 1976.