IOP Conf. Series: Materials Science and Engineering **308** (2018) 012041 doi:10.1088/1757-899X/308/1/012041

Fatigue crack growth behaviour of semi-elliptical surface cracks for an API 5L X65 gas pipeline under tension

M S Shaari [*1], M R M Akramin [1], A K Ariffin[1], S Abdullah[1], M Kikuchi[2]

[1]Department of Mechanical and Materials Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, MALAYSIA
[2]Tokyo University of Scince, 2641 Yamazaki, Noda, Chiba 287-8510, JAPAN, Phone: +603-8921 6012

[*]E-mail: mohdshamil.shaari@yahoo.com

Abstract. The paper is presenting the fatigue crack growth (FCG) behavior of semi-elliptical surface cracks for API X65 gas pipeline using S-version FEM. A method known as global-local overlay technique was used in this study to predict the fatigue behavior that involve of two separate meshes each specifically for global (geometry) and local (crack). The pre-post program was used to model the global geometry (coarser mesh) known as FAST including the material and boundary conditions. Hence, the local crack (finer mesh) will be defined the exact location and the mesh control accordingly. The local mesh was overlaid along with the global before the numerical computation taken place to solve the engineering problem. The stress intensity factors were computed using the virtual crack closure-integral method (VCCM). The most important results is the behavior of the fatigue crack growth, which contains the crack depth (a), crack length (c) and stress intensity factors (SIF). The correlation between the fatigue crack growth and the SIF shows a good growth for the crack depth (a) and dissimilar for the crack length (c) where stunned behavior was resulted. The S-version FEM will benefiting the user due to the overlay technique where it will shorten the computation process.

1. Introduction

During the past 40 years, there have been many observations made on surface cracks under cyclic tensile loading. Since then, the continuity of research to evaluate the structural integrity in mechanical components vastly spread including the gas pipeline. It is very essential for oil and gas industry because the gas pipelines are viable to the fatigue loading that comes from the ground and vehicles [1]. The fact that the gas pipelines are buried under the ground is enough to include such environmental affect to the structure. The results of this environmental defect will cause the gas to leaks and lead to fire hazards and endangering human beings.

The API 5L X65 are one of the most commonly use type of material in oil and gas industry [2], thus it is considerable the importance of this study to the society generally and the industry specifically. The deterioration of an engineering structure happens when a cyclic loading presence on a period of time. The influence of other aspect such as corrosion, creep and material defect can add to the total cause. However, for a structure that happens to experience a direct interaction with the loading coming from energy generated from the oil and gas or even the environment aggressiveness (e.g. earthquakes, heavy vehicle on the ground) [3].

Numerous researches have conducted many studies for structural integrity for gas pipeline. However the involvement of surface cracks in gas pipeline is still expandable especially when it is related with

IOP Conf. Series: Materials Science and Engineering **308** (2018) 012041 doi:10.1088/1757-899X/308/1/012041

the S-version FEM. This method was developed by Fish in year 1992 with the main objective, “to improve the quality of the finite element calculation in the regions of unacceptable errors” [4]. Since then, several researches were and still working in this area of specialty including Kikuchi and his team. It is widely accepted in fatigue and fracture mechanics field for example, since the last five years the number of publications increase progressively in varies topics from weld-heat-affected zone [5], internal cracks [6], multiple cracks [7], mixed mode cracks [8], heterogeneous material [9] and many more.

The objective of this study is to predict the fatigue crack growth (FCG) behavior of semi-elliptical surface cracks for API X65 gas pipeline using S-version FEM under tension loading.

2. S-version FEM Simulation Procedure

This section will be presenting the procedure to conduct the computational analysis using the S-version FEM. In this research study, the main material is the API 5L X65. However, the other materials are used such as SUS 304 and ASTM A533B to compare the fatigue behavior among the materials. Note that the load and geometry of the plates for all materials are similar. The API 5L X65 material used in this research study was acquired by a Malaysian owned oil and gas company. In order to attain the material properties, the monotonic test was conducted and consist of 223 GPa for the modulus Young’s (E), 0.3 for the poisson ratio (υ), 472 MPa for yield and 648 MPa. The original concept of S-version FEM that was developed by Fish emphasized on the superimposed between local and global meshes.

Figure 1 shows a single crack referring to local mesh and it is then overlay together with a finite plate referring to the global mesh. Figure 2 shows the local and global meshes that were modeled in FAST using 20-node hexahedral elements. FAST is a pre-processing program written in C++ language. The geometry of the finite plate is 200mm by 200mm with a thickness of 20mm. The crack’s length is 20mm and the depth is 4mm. The geometry of the local and global in this research study is using a specific ratio such as a/c of 0.4, c/b of 0.1, c/h of 0.1 and a/t of 0.2 where a is the crack depth, c is the crack length, b is the plate width, h is the plate length and t is the plate thickness.

Therefore, later on any computational can be performed by following the standard. In order to design a tension loading, the bottom of the plate is fixed in all direction while the upper side pulled with uniform load of 10MPa as shown by figure 3. The results of the displacement deviations in figure 4 validate the tension loading. Notice that the deviation is in y direction similar to the load applied.

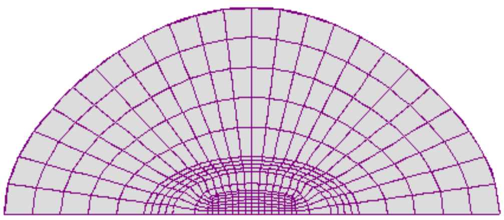


Figure 1. Local semi-elliptical surface crack

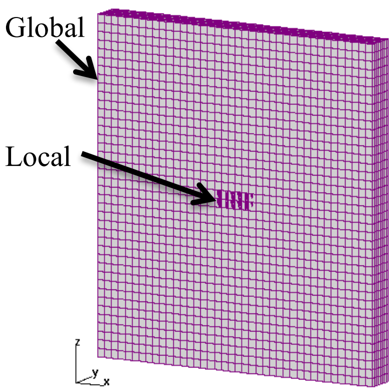


Figure2. Geometry of plate combines with the crack

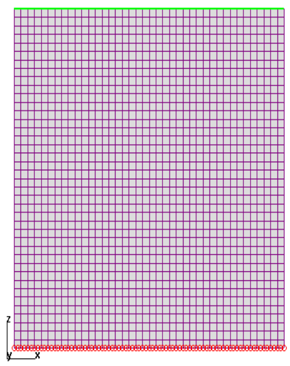


Figure 3. Global with boundary condition

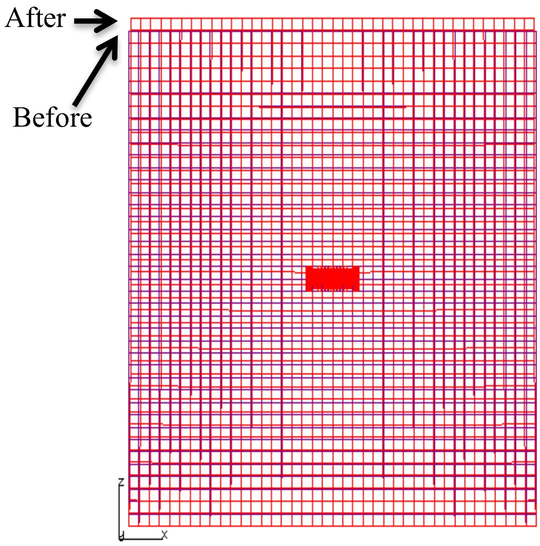


Figure 4. Displacement of global and local

3. S-version FEM Computational Results

The results of semi-elliptical surface cracks and the fatigue crack growth behavior will be discussed in this section. Figure 5 shows the semi-elliptical surface cracks according to the beach marks for all three types of materials. There are no notable differences between all types of materials accept the crack grows in plausible state. Figure 1 and figure 2 shows the axis for the crack and the propagation of the crack consists of two which are crack depth (a) and crack length (c). As for the center of the crack, it is noticeable at zero coordinate and the total length of the crack is 20mm.

The results produced by S-version FEM significantly showed vast crack propagation for the crack depth (a) and only small extent for the crack length (c). This is supported by [10] in discussing the shape of the surface cracks differ subjected to loads such as tension loading and bending loading. The effect of loading mode for the surface cracks influenced the evolution of the crack shapes prediction. It is because of the nature of the boundary and geometry of a rectangular plate most likely will be influencing the loading mode. The crack length (c) experiencing stunned development compare to the crack depth (a). To justify why the crack depth (a) propagates vastly than crack length (c), it can be reasoned by referring Figure 6. The equivalent stress intensity factors (Keq) is showing a better slope for the crack depth compare with the crack length. It is known in general that the SIF represent the crack growth movement and this explain the phenomenon.

It is norm to define the Paris exponents from the fatigue crack growth behavior especially from the experimental results. On the other hand, the S-version FEM already considers all the values before the simulation as inputs needed to compute the fatigue crack growth. Nonetheless, the purpose of the fatigue crack growth rate graph is still needed to observe the behavior especially when comparing the crack depth and crack length.

Figure 7 shows the cracks versus life cycles and as predicted by the fatigue crack growth rate graph, the crack length undergoing stunned growth unlike the crack depth. The increment for the crack growth is much smoother and proportional with the life cycles. Include in this study is the normalized SIF behaving along with the angular direction as shown in Figure 8. Notice the degree of angle (ϕ) representing the 90 degree of angular direction for the SIF. From the results, since the loading was applied uniformly, the SIF extend and propagate starting from 0 degree to 90 degree as can be seen from Figure 8. Note that the total angular direction is only 180 degree, hence the reason why the graph only consider it to be 90 degree. The results was normalized using Okada [11] and the calculations was based on the author concept.

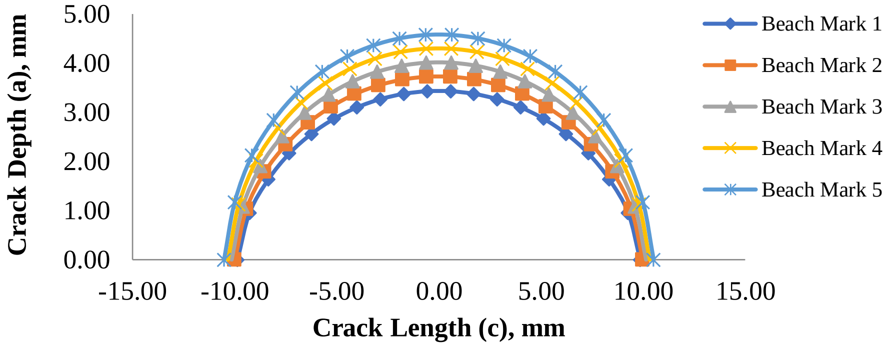
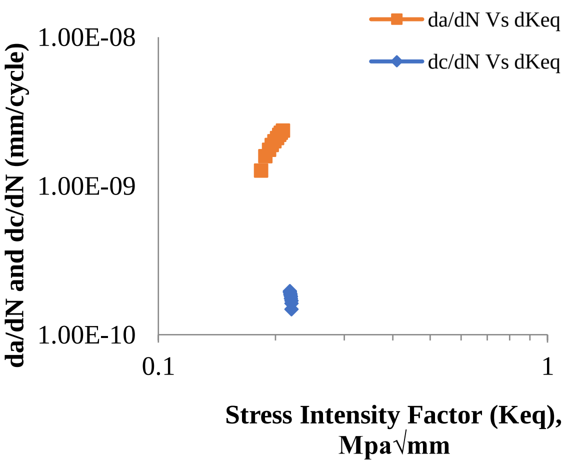
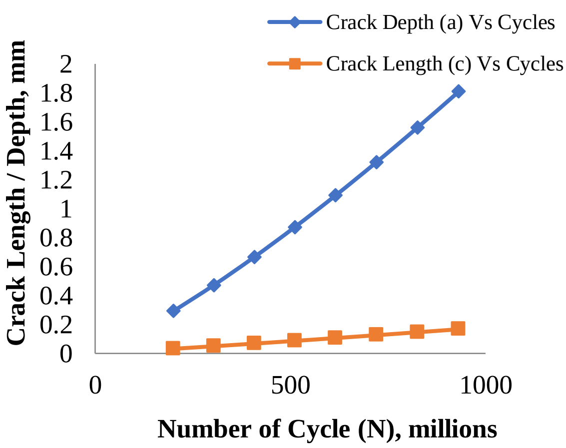


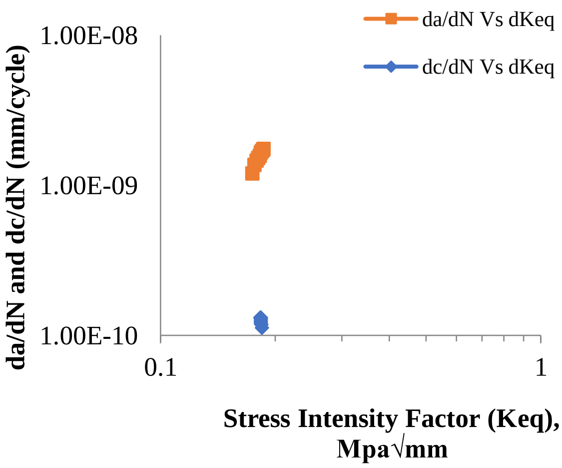
Figure 5. Fatigue crack growth for API X65 according to the beach marks.



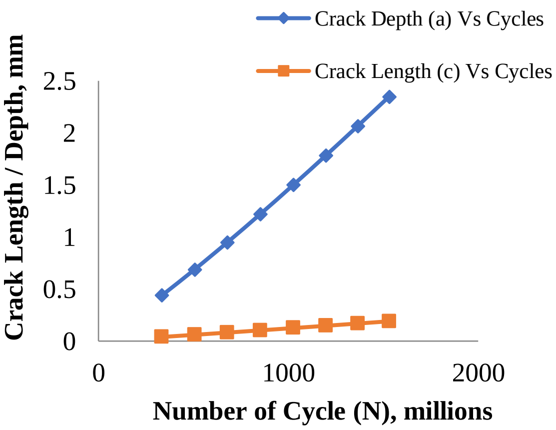
(a)



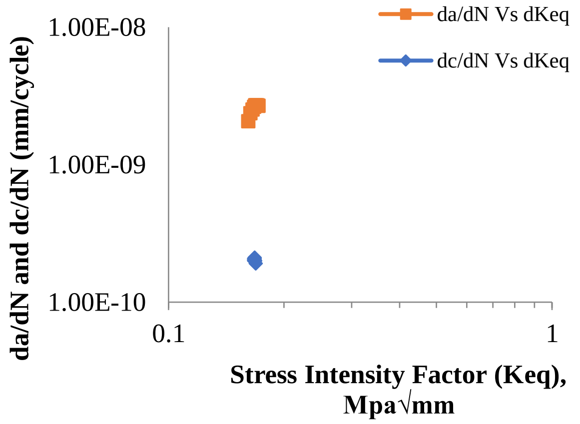
(a)



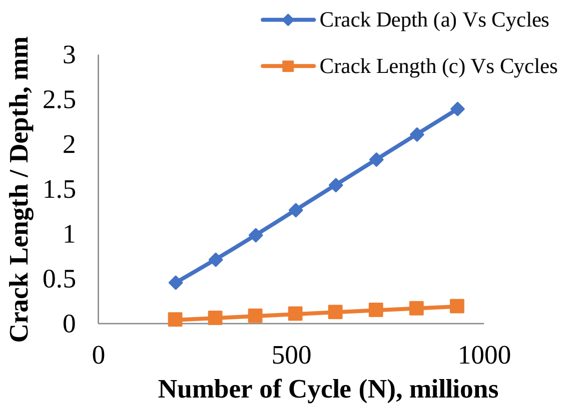
(b)



(b)



(c)



(c)

Figure 6. Comparison of FCGR between crack depth and crack length for (a) API X65, (b) SUS 304 and (c) ASTM A533B.

Figure 7. Comparison of crack length and crack depth for (a) API X65, (b) SUS 304 and (c) ASTM A533B according to the number of cycles.

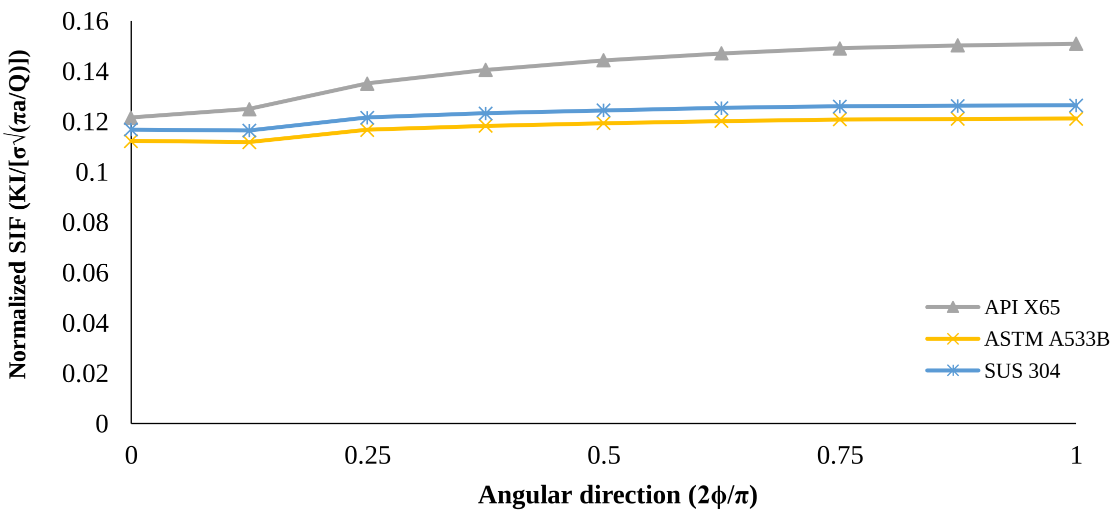


Figure 8. Comparison of normalized SIF according to the angular direction.

4. Conclusion

The prediction of the fatigue crack growth behavior of semi-elliptical surface cracks for API 5L X65 gas pipeline using S-version FEM under tension loading was performed successfully. The normalized SIF does very essentials especially if the research study related with the surface cracks and by comparing with different materials gave a significant value to the research conducted.

Acknowledgements

The author would like to acknowledge the Universiti Kebangsaan Malaysia (UKM), especially the laboratory of computational & experimental mechanics (CEM) for allowing the research to be conducted using the high performance computer (HPC).

References

[1] Hong S W, et al. 2015 Fatigue life prediction for an API 5L X42 natural gas pipeline. *Engineering Failure Analysis* In Press 2015(0)

IOP Conf. Series: Materials Science and Engineering **308** (2018) 012041 doi:10.1088/1757-899X/308/1/012041

[2] Fatoba O and Akid R 2014 Low Cycle Fatigue Behaviour of API 5L X65 Pipeline Steel at Room Temperature *Procedia Engineering* **74**:0 pp 279-286
[3] Mansor N I I, et al. 2014 A review of the fatigue failure mechanism of metallic materials under a corroded environment *Engineering Failure Analysis* **42** pp 353-365
[4] Fish J 1992 The s-version of the finite element method *Computers & Structures* **43**:3 pp 539-547
[5] Kikuchi M, et al. 2012 Crack growth analysis in a weld-heat-affected zone using S-version FEM *International Journal of Pressure Vessels and Piping* **90–91** pp 2-8
[6] Wada Y, et al. 2014 Fatigue growth of internal flaw: Simulation of subsurface crack penetration to the surface of the structure *Engineering Fracture Mechanics* **123** pp 100-115
[7] Kikuchi M, et al. 2010 *Closure Effect on Interaction of Two Surface Cracks Under Cyclic Bending* ASME 2010 Pressure Vessels and Piping Division/K-PVP (Bellevue, Washington, USA.: ASME)
[8] Kikuchi M, Wada Y, Suga K, 2011 Surface crack growth simulation under mixed mode cyclic loading condition *Procedia Engineering* **10** pp 427-432
[9] Kikuchi M, et al. 2014 Fatigue crack growth simulation in heterogeneous material using s-version FEM *International Journal of Fatigue* **58** pp 47-55
[10] Lin X B and Smith R A 1999 Shape evolution of surface cracks in fatigued round bars with a semicircular circumferential notch *International Journal of Fatigue* **21**:9 pp 965-973
[11] Okada H., et al. 2005 Three dimensional virtual crack closure-integral method (VCCM) with skewed and non-symmetric mesh arrangement at the crack front *Engineering Fracture Mechanics* **72**:11 pp 1717-1737