Stress Intensity Factor Estimation for Straight Base Component of Two Dimensions

Siddharth Bhadauria[1]

[1]*B-tech, Jaypee university of Engineering and Technology, Guna*

Abstract

Failure in industrial term is known as not to perform the intended or desired work. For a design engineer it is very important that a part does perform its intended job efficiently and more reliably. In nuclear power plant there are various pipe lines which carries pressurized fluid and with time under certain conditions these repeated and cyclic loads can cause a fracture inside the pipe wall. Design engineer has to ensure that condition like this doesn't occur frequently because there are so much at the stake. Now these fracture will occur because of the constantly repeating cyclic loads but measuring the extent to which a pipe can function properly can make a very big difference. System level computer modeling of complex nuclear system is increasingly becoming trend due to availability of advanced computer programs and multi processer based parallel computing hardware and software[1]. Computer based fracture analysis helps in mechanics of the material and computing the different area of the fracture growth. The present level FEA code also allows determination of other field variable. Furthermore, advances in FEA tools for 3-D fracture mechanics and crack propagation allow accurate prediction of the structural integrity of reactor components under severe accident conditions in reactor pressure vessels and other primary pressure boundary components. Most of the literature on fatigue modelling has focused on improving the stress-life data and related empirical fatigue design curves [2] for estimating fatigue life given the stress/strain state of a reactor component. A few studies [3] have emphasized the more mechanistic aspects of fatigue life prediction. For predicting fatigue life estimation it is necessary to understand the crack growth mechanism. Studies related to the crack propagation at constant amplitude loading in cyclically loaded structure is hardly found in most practical applications, though there are some studies done over constant amplitude loading like Paris equation[4] and Forman/Mettu[5].

Keywords; nuclear power plant, stress intensity factor (SIF), austenitic stainless steel (ASS), LEFM, fatigue life, Paris law

1. Introduction

Because of the high end mechanical property of ASS, it is widely used as a nuclear power plant component. But there are many high tensile residual stresses in it,which causes crack [6]. In any NPP it is considered that pressure distribution inside the pipe component is uniformly distributed but we cannot say that it actually happens inside the component. There occur so many stresses and variable load which causes residual stress to grow over there and make a crack tip which is actually caused by the SIF. This crack tip with increasing time propagates the crack formation and from the occurring of the crack to the total fracture in the surface of the component is called as fatigue failure. These fatigue failure are very harmful not only for us human lives but also for the environmental condition apart from that it also causes loss of money and lives of the employee and people living around the plant. In any NPP it is very important to ensure the safety of the employee of that plant and also the environment that's why every component of the nuclear power plant should be checked on the regular basis because components of the NPP often undergoes various type of load which causes residual stresses on the surface of the pipes. These pipes are often welded at certain cross sections. Now the properties welded part differs from the parent metal to certain extent. Here we are trying to elaborate a review regarding the effect of residual stresses and SIF on the pressurised weld base component.

Recent researches has said that because of thermal ageing embrittlement it tend to lose toughness [7,8,9]. Now from time to time these component must be checked and inspected but this takes a lot of time, resources, workers and more importantly money. However due to the inherent complexity of the welding there is a significant difference between the reading by analyst and FFS codes the effect of residual stresses on the weld should be evaluated rigorously before thermal ageing take place. Apart from previous reasons because of the stress concentration life of the welded joint decreases [10]. This stress concentration is maximum at weld toes and weld root because of the variation of the shape of weld. Hence for finding the fatigue life of such structures evaluation of stress intensity factor is very important. For measuring the fatigue life it is really important to understand the linear elastic fatigue mechanism because it actually helps us in measuring the fatigue life of an y component. For doing that we need to find many constraint like residual stresses which eventually lead us to stress intensity factor, expression for the fatigue crack growth rate and finally initial and final crack size. Paris law creates a relationship between crack growth rate and SIF. Nowadays notch stress intensity factor which also is an extension of the stress intensity factor which allow us to know the stress intensity feild at the surface of the component

1.1 Fatigue

Fatigue is one of the principal modes of failure to be considered in the design of components and structures subjected to repetitive types of loads, e.g. Automobile components, railway track components and rolling stock bridges. Offshore structures, ships pressure vessels, handling equipment like cranes, excavators and pipelines, aircraft and space structures are some of the components/structures, which are generally subjected to repetitive loads during their lifetime [11, 12].The crack growth study, one should consider all the possible crack growth mechanisms such as corrosion, erosion, fatigue, creep, flow induced vibration etc [13,14,15]. Whichever may be operative for the particular heavy water reactor (HWR), Primary heat transport (PHT) piping systems, fatigue is the only crack growth mechanism which cannot be totally ruled out. In materials science, fatigue is the weakening of a material caused by repeatedly applied loads. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values that cause such damage may be much less than the strength of the material typically quoted as the ultimate tensile stress limit, or the yield stress limit.

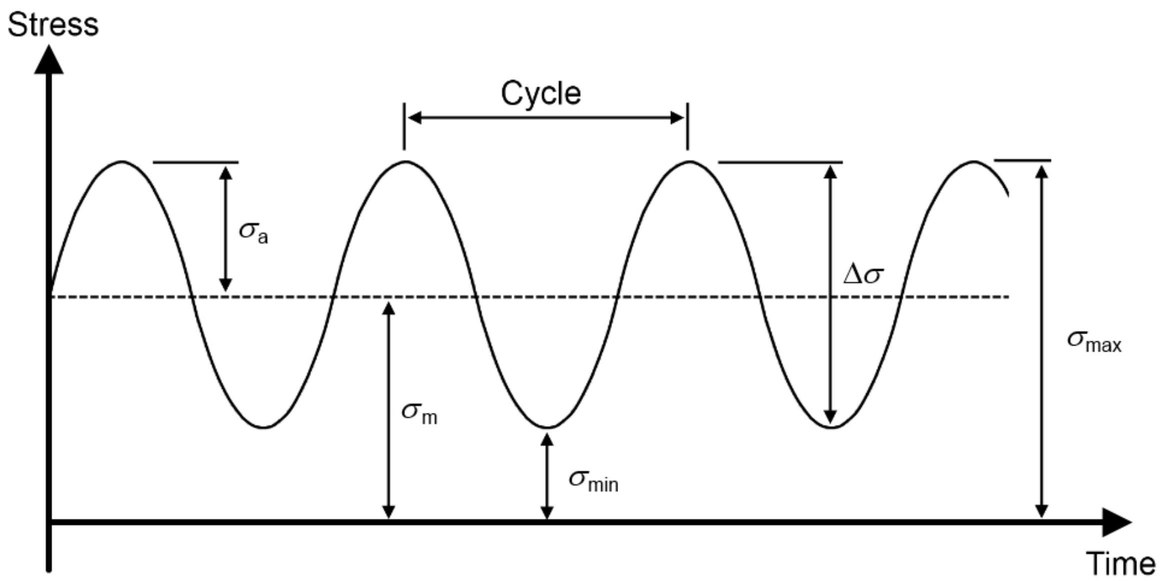
Fatigue occurs when a material is subjected to repeat loading and unloading. If the loads are above a certain limit, microscopic cracks will begin to form at the stress concentrated area or point such as the surface, persistent slip bands (PSBs), interfaces of constituents in the case of composites, and grain interfaces in the case of metals. Hence a crack will reach a critical size where the crack will propagate suddenly and the structure will fracture. The shape of the structure significantly affects the fatigue life, square holes or sharp corners will lead to elevated local stresses where fatigue cracks can initiate. Round holes and smooth transitions or fillets will therefore increase the fatigue strength of the structure.

Process of completely failing of the mechanical component can be divided into three stages

1. During a large number of cycles, the damage develops on the microscopic level and grows until a macroscopic crack is formed.
2. The macroscopic crack grows for each cycle until it reaches a critical length.
3. The cracked component breaks because it can no longer sustain the peak load.

The second process in certain components happen really fast so all we can see a crack moving with a rapid pace. The detailed knowledge about the last two stages can be found in fracture mechanics, fatigue mainly applies to the first stage rest of the two stages are mainly for the failure and the mechanics related to it.

Under the influence of a non constant external load, the state in the material also varies with time. The state at a point in the material can be described by many different variables such as stress, strain, or energy dissipation. The fatigue process is typically viewed as controlled by a specific such variable. A load cycle is defined as the duration from one peak in the studied variable to the next peak. In a general case, all cycles do not have the same amplitude. For a superficial discussion, it can, however, be assumed that the fatigue-controlling state variable has the same value at the start and end of each load cycle. In elastic materials, a cyclic load causes a periodic-cyclic stress response. For such cases, the load cycle is easily defined. This is illustrated by the figure below, where stress is the fatigue-controlling state variable.



The stress varies between a *maximum stress,* σ_{max}, and a *minimum stress,* σ_{min}, during a load cycle. In the field of fatigue, the variation in stress is often defined using the *stress amplitude,* σ_a, and the mean stress, σ_m. Further, variables defining the *stress range,* $\Delta\sigma$, and the *R*-value are frequently used to describe a stress cycle. The relation between the different fatigue stress variables is

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min}$$

$$R = \frac{\sigma_{max}}{\sigma_{min}}$$

1.2. Stress Intensity Factor (S.I.F)

As one can perceive through many mechanical failures occurring nowadays it can be said that these failure occurs because of the propagation of fatigue crack frequently in many structures and component. For instance Chernobyl Disaster in 1986. Prediction of fatigue life is very important for supporting frame of wind turbines, offshore machineries, nuclear reactor where high cycle major fatigue is concern. Welding is very convenient and inexpensive way of joining two or more different components in such kind of facility. With the rapid development in the industry and our never ending hunger for energy nuclear power plants have came into existence. These plant though very efficient in terms of producing electricity carries risk of failing which has been explained earlier. Therefore taking full care of the power plant and its component has to be a main concern of any design engineer and with rapid development of the latter, its components are now given more and more attention.

Now as we have discussed earlier about the effect on the welded joint in a nuclear power plant we can say that at many cross sections there is a chance of welding of two dissimilar metal which causes us to show different material properties in the Heat Affected Zone. In this heat affected zone because of non linear temperature distribution and coefficient of thermal expansion there occur some residual stresses in heat affected zone. These residual stresses actually propagates the crack propagation and stresses at the crack tip is called as Stress Intensity Factors. For problems related to crack, Paris law is actually used for evaluating crak growth. However Paris law is actually based upon LEFM approach which helps in evaluating the crack growth and fatigue life does not contributes in the evaluation of SIF accurately [24]. Hence use of FEA has been introduced nowadays. As 2-dimensional modeling in FEA is easier and hence less accurate that's why use of 2D modeling for a pressurized base weld component (PBWC) is restricted. 3-Dimensional modeling is used for the PBWC because of the kind of the structure PBWC possess. A pipe is a 3D model of a cylinder. We are not making analysis on a 2D projection of a cylindrical pipe. Though 3D modeling is tough and time taking, it gives accurate and best result according to the problem formulated.

FEM requires special techniques and nowadays for saving time people are using the hybrid between between 2D and 3D model. Though conditioned based maintenance system are in trend in any nuclear power plant but still a more accurate working systems and software are still needed as it does not tell us the information regarding the fatigue failure and crack propagation accurately. Apart from that these softwares are the kind of software which works according to the specific set of plan, the do not self analyze the condition and tell the operator the assessment of the situation regarding the components in the nuclear power plant or in any thermal power plant. Also crack propagation actually takes place at the surface of the pipes as the fluid flows through it at very high speed and temperature which causes repetitive fluctuating loads over the surface of the pipe. Thus pipe after some time start showing the sign of fracture. It is same as when gunshot is fired through a barrel though the fluid does not flows through It as fast as a bullet but then again it actually flows through it with some speed at very high temperature leaving the pipe in a very bad position. Hence it was proposed to increase the allowable pressure of the cylindrical pipe component so as to increase the pipe's life cycle. This phenomenon is same as a autofrettage which tends to take place in the gun barrel. It was first discovered by the Jacob of the French artillery in 1907. He said that the allowable pressure of the gun barrel must be increased so that shot can be fired to a great distance.

Here our aim is not to fire the fluid to great distance but to minimize the residual stresses at the surface of the pipe. And this is the normal ASS pipe we are talking about not the welded joint between the cross section of a pipe. Where because of the coefficient of expansion residual stress emerge. And it has been proved before that these residual stresses actually influence the crack propagation. Beside even if we increase the size of the cylindrical pipe component or any other component it will take more space which is not useful and not ideal already. For design engineer using of the floor space area efficiently is very important as it reduces the cost of the transportation. Nowadays autofrettage has been developed further for producing better result not only in the field of weaponry but also in the field of cylindrical pressure vessel.

We know pressure vessels is also a kind of a cylinder but a close one from both of the ends. Cylindrical pipes however are open in both the direction to facilitate the flow of fluid in a nuclear power plant. Therefore these cylindrical structures are called as thin walled structures. Therefore crack initiation actually takes place in the radial direction or axial direction because of the hoop stresses being larger in magnitude in that direction. The structural integrity is actually based upon the Stress Intensity Factor in order to bring out the crack growth and its life cycle hence it is really important to perform the proper FEA test on it in order to get the accurate result. In the calculation of stress intensity factor various parameters should be calculated like S.Suresh et al.[16] explained the need of calculating the geometry correction factor for the purpose of better accuracy in result. However most of the results are limited to the Mode-I of the failure which is the tensile stresses normal to the surface of the specimen. Mode II and Mode III of the failure have been neglected by most of the researches because of the hard and time taking calculation of the FEA experiment. Calculation of Stress intensity factor works best under high constraints because if not this may lead to the deviation of the crack tip from the SSY solution hence a high constraint SIF would lead to a better and accurate result for the purpose of evaluating of the fatigue crack life[26]

2. Terminology and Methodology

Two kinds of fatigue loads are encountered

- Constant amplitude load
- Variable amplitude load

Load on a locomotive axle is of constant amplitude whereas fluctuating wind loads on a wing of an aircraft is of variable amplitude. In certain cases both type of loads can be super imposed on the component.

For the constant amplitude fatigue load the terminology has been explained above. However, for variable amplitude load the terminology is as follows

$$K_{max} = f(\alpha/w)\sigma_{max}(\pi a)^{1/2}$$

$$K_{max} = f(\alpha/w)\sigma_{min}(\pi a)^{1/2}$$

Where f(α/*w*) is the geometric factor for crack length a and component width w in most of the cases, dependence of f(α/*w*) on crack length a is of secondary nature as of the $(a)^{1/2}$ dependence. Some designer prefer not to consider variation of f(α/*w*) to keep the calculation simple. The difference of the K_{max} and K_{min} is an important parameter for determining crack growth and is oftenly described as

$$\Delta K = K_{max} - K_{min}$$

Another parameter ratio R is also used and defined as

$$R = \sigma_{max} / \sigma_{min}$$

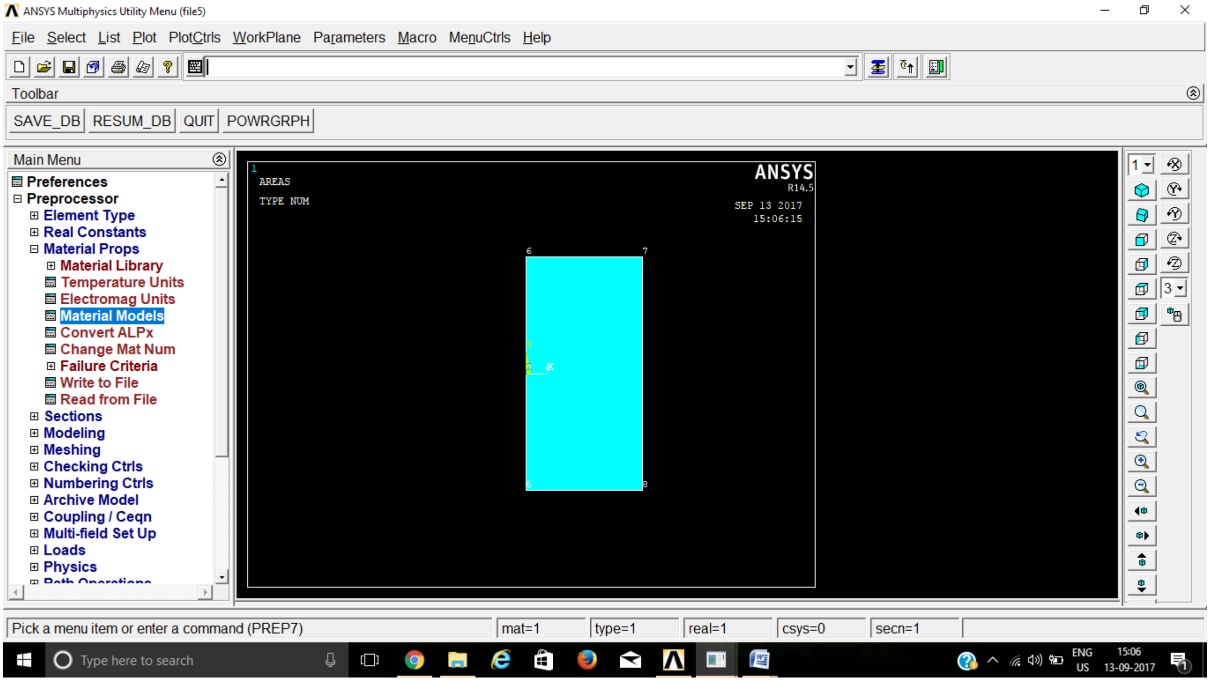
There are three catagories of R , positive, zero and negative as shown in the below figure. Positive R is tension-tension fatigue wheras R negative is represented as tension-compression fatigue

For negative stress ratio, compressive stress loading is not likely togrow the crack and therefore some investigators treat this case as the one having R=0. However in sophisticated analysis R=0 and R<0 be treated differently. A fatigue crack may be initiated at an existing notch, an inclusions or a surface. It has been usually observed that initiation requires a large number of load cycles. Once the crack is initiated it grows by some distance in every cycle initially with extreamely small growth per cycle. As the crack starts becoming longer, the rate of propagation per load cycle, da/dn, also increases. Obviously very small cracks can not be detected by available not distructive test techniques. No. Of cycles consumed to initiated to initiated the crack and then grow it to a smallest possible detectable length is known as initiation life N_i. The detectable crack in most cases still very much sub critical and needs to be grown further under the fatigue loads. No. Of cycles required to grow the smallest detectable crack to the critical size is known as propagation life N_p. thus, the total life becames

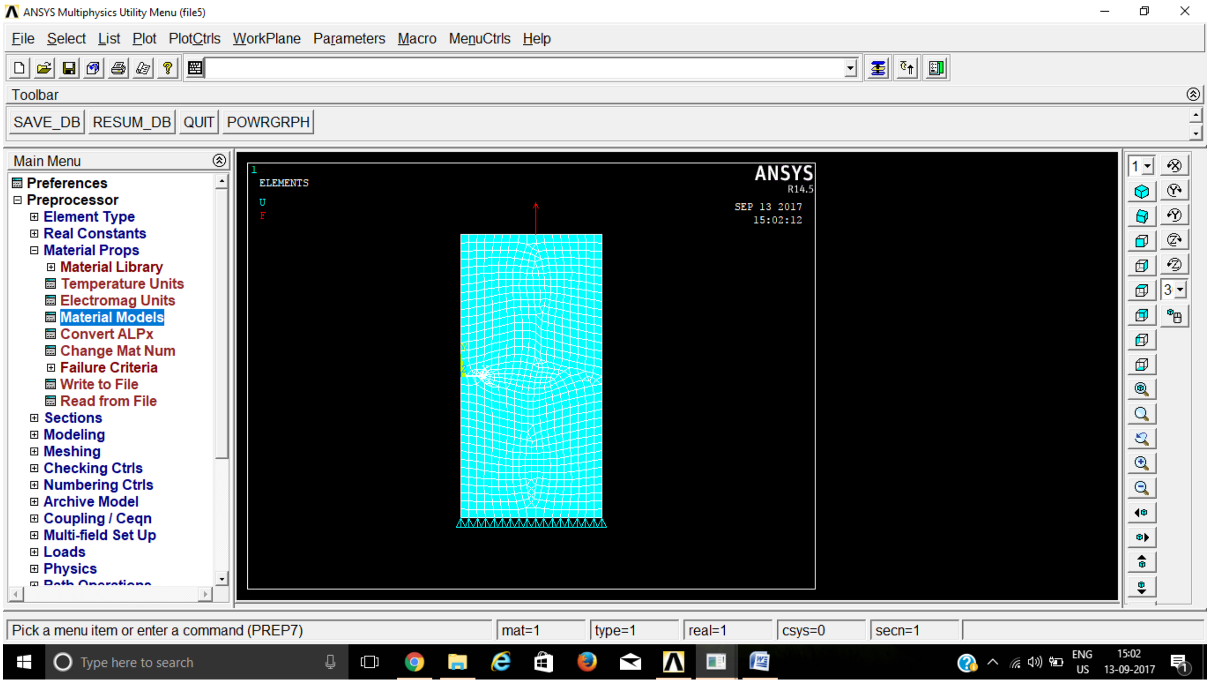
$$N = N_i + N_p$$

3. Experimentation and result

Experimented model of a Al6061 plate



This is the meshed model of the Al6061 with the boundary conditions applied as it can be seen from the figure.



at different depths the stress intensity factors of the given model is as follows

K_s	K_d	dN	dN
10.532	0	44507	44507
13.563	0	42386	86893
14.225	0	40178	127071
15.171	0	37984	165055
15.654	0	33655	198710
16.10013	0	27569	226279

Here dN shows the number of cycles after which it fails

4. **Result and conclusion**

Here we conclude that stress intensity factor helps us in finding the fatigue life of the material before which it fails. This work also concludes that it is needed more and more material to understand the basic nature of the stress intensity on the different material and under different circumstances.

5. References

[1] Chen et al., 2014a; Qian and Niffenegger, 2013a,b, 2015; Keimet al., 2001; González-Albuixech et al., 2014.

[2] Chopra and Shack, 2007; Chopra and Stevens, 2014; Japan Nuclear Energy Safety Organization, 2011

[3] Kalnins et al., 2015; Rudolph et al., 2011; Gilman et al.,2015; Shit et al., 2013; Yun and Shang, 2011; Pirondi and Bonora,2003; Chakherlou and Ajri, 2013

[4] P.C. Paris, F. Erdogan, A critical analysis of crack propagation laws. In: Journal Basic Engineering 85 1963, p. 528-534

[5] R.G. Forman, S.R. Mettu. Behavior of surface and corner cracks subjected to tensile and bending loads in Ti-6Al-4V alloy. In: Fracture Mechanics: 22nd Symposium, Vol. 1 (Eds H.A. Ernst, A. Saxena, D.L. McDowell), ASTM STP 1131, American Society for Testing and Materials, Philadelphia 1992, 519-546

[6]Atrens A, Hoffelner W, Duerig TW, Allison JE. Subsurface crack initiation in high cycle fatigue in Ti6AL4V and typical martensitic stainless steel. Scr Metall 1983;17:601–6

[7] Wöhler, A., Über die Festigkeitsversuche mit Eisen und Stahl, Zeitschrift für Bauwesen, Vol. 20, 1870, pp. 73-106.

[8] Basquin O. H., Proc. ASTM 10, 625, 1910.

[9] The International Institute of Welding, *Stress Determination for Fatigue Analysis of Welded Components*, Abington Publishing, Cambridge, England, 1995

[10] punit arora et al 'fatigue crack growth behaviour in pipes and elbows of carbon steel and stainless steel materials '

[11] J. Van Wittenberghe , P. De Baets , W. De Waele , T.T. Bui , G. De Roeck 'Evaluation of fatigue crack propagation in a threaded pipe connection using an optical dynamic 3D displacement analysis technique'

[12]Taheri S. Some advances on understanding of high cycle thermal fatigue crazing. ASME J Press Vessel Technol 2007;129:400–10.

[13] Le Duff A, Tacchini B, Stephan JM, Fissolo A, Vincent L. High cycle thermalfatigue issues in RHRs mixing tees and thermal fatigue test on a representative304L mixing zone. PVP2011-57951, Baltimore, Maryland, USA; 2011.

[14] Sonsino CM. Effect of residual stresses on the fatigue behavior of welded jointsdepending on loading conditions and weld geometry. Int J Fatigue2009;31:88–101.

[15] Ferro P, Berto F, James MN. Asymptotic residual stresses in butt-welded jointsunder fatigue loading. Theoret Appl Fract Mech 2016;83:114–24.

[16] Taheri S, Julan E, Tran XV. Fatigue crack growth and arrest under high-cyclethermal loading using XFEM in presence of weld residual stresses. In: Proc of5th conference on crack path (CP-2015) September, Ferrara Italy; 2015.

[17] Sbitti A, Taheri S. Crack arrest in high cycle thermal fatigue. Nucl Eng Des2010;240(1):30–8.

[18]J. Colin, A. Fatemi, Variable amplitude cyclic deformation and fatigue behaviour of stainless steel 304L including step, periodic, and randomloadings, Fat. Fract. Eng. Mat. Struct., 33 (2010), 205 – 220.

[19] A. Palmgren, Die Lebensdauer von Kullagern, Zeitschrift des Vereins Deutscher Ingenieure, 1924, 339–341, (In German).

[20] M.A. Miner, Cumulative damage in fatigue, J.Appl. Mech., 12 (1945), 159–164.

[21] T. Svensson, Fatigue testing with a discrete-time stochastic process, Fat. Fract. Eng. Mat. Struct., 17(1994), 727 – 736.

[22] P. Johannesson, M. Speckert (Eds.), Guide to Load Analysis for Durability in Vehicle Engineering, Wiley: Chichester, 2013.

[23] B. F. Langer, Design of Pressure Vessels for Low-Cycle Fatigue, ASME J. Basic Eng., 84 (1962), 389–402.

[24] Kalnins et al., 2015; Rudolph et al., 2011; Gilman et al.,2015; Shit et al., 2013; Yun and Shang, 2011; Pirondi and Bonora,2003; Chakherlou and Ajri, 2013