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Life Estimation of Piping Components of Nuclear Power Plant for Safe Operations – A Review

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ABSTRACT
In the present review paper, various researches results developed so far are discussed. Particular emphasis will be given to the prediction of the crack growth stages, stress intensity factor, J-integral, number of cycles for crack having a key role in the overall fatigue life prediction. All considered approaches (Leak before break, linear elastic fracture mechanics, elastic plastic fracture mechanics etc.) are applicable to life prediction of nuclear power plant (NPP) piping components, to enable us for enhancing the NPP piping component life for safe operation.

Keyword – NPP (nuclear power plant), stress intensity factor (SIF), fatigue crack growth (FCG)

I INTRODUCTION

Fatigue is a major source of product failure. Most products exposed to repeated cyclic loadings will eventually fail. Caused by repeated or otherwise varying loads, fatigue is a result of repetitive stress over time, as microscopic changes become cracks that cause malfunction.

As a result, making informed design decisions to improve your product's durability is increasingly important. Product failure can result in recalls, high repair costs, legal liabilities.

Fatigue analysis for nuclear components in the design phase uses covering (enveloping) loads and is conducted to demonstrate that the cumulative usage factor, CUF, is less than one. The loads, expressed in terms of fluid system pressure and temperature transients, are defined in the equipment technical specification, and consider a conservative prediction of the magnitude and frequency of these fluid transients to occur during various service conditions.

The major prerequisites for any subsequent fatigue assessment are the accurate component stress analysis and the identification of relevant cycles, using highly qualified and efficient cycle counting methods.

The main characteristics of cyclic loading are the frequency of occurrence and the amplitude. Both of these can remain constant or vary, the latter option describing much more realistically actual cyclic loading conditions than the former.

II FATIGUE CRACK

If the components are subjected to a fluctuating load of a certain magnitude for a sufficient amount of time, small cracks will nucleate in the material. Over time, the cracks will propagate, up to the point where the remaining cross-section of the component is not able to carry the load, at which the component will be subjected to sudden fracture. This process is called **fatigue**, and is one of the main causes of failures in structural and mechanical components. In order to assess the safety of the component, engineers need to estimate its expected lifetime. The fatigue life is the sum of the number of loading cycles required for a fatigue crack to initiate, and the number of cycles required for the crack to propagate before sudden fracture occurs.

The fatigue life of a structural component under cyclic loading can be considered to consist of two phases, which are the crack initiation life followed by a crack growth period until failure. This can be represented in a block diagram.

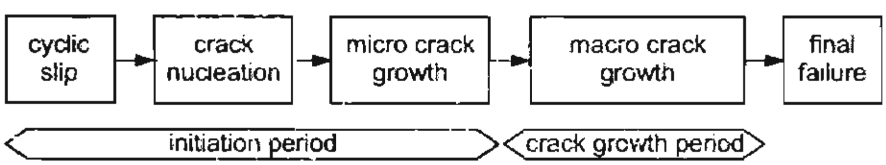

Fig. The different phases of the formation and growth of a fatigue crack

Crack growth is an atomic level breakage and breaking of the bonds linking the atoms and gathering of dislocations (imperfections in the atomic structure). Thus, new surfaces are created in the solid as the crack nucleates and continues to grow. It is not certain that the fatigue crack will continue to grow.

By assuming a small size for predicting the growth life, it is possible to neglect the initiation life for the fatigue life estimation. It is relatively easy to quantify the growth life because the crack growth rate has been shown to correlate with the stress intensity factor (SIF), and the experimental technique for obtaining the material constants for growth prediction has been standardized.

For the analysis of fatigue crack growth, the Paris law has proved to be a simple, accurate and robust approach where knowledge of stress intensity factor is enough to predict the growth rate of edge and through-thickness cracks. In order to analyses the growth of surface cracks under cyclic loading, it has been generally accepted to apply the Paris law for the deepest and the surface points of the crack and then assume a semielliptical shape for the crack.

III NUCLEAR POWER PLANT PIPING COMPONENTS

Actual stress analysis of these components are required for reliable estimation of fatigue crack growth behavior, stress intensity factor and residual life, as most of the failures in the piping components are due to fatigue loading. An alternate fail safe design philosophy such as leak-before-break (LBB) based on fracture mechanics concepts is adopted to demonstrate that piping components will not fail to catastrophic manner. Investigation on fatigue crack growth (FCG) Of pipes and elbows with postulated part through flaws for the qualification of LBB design criteria.[2]

Fatigue is one of the principle modes of failure to be considered in the design of components and structures subjected to repetitive types of loads. This work will be carried out for pipe components – pressure based straight Component (PBSC) and pressure weld straight components (PWSC), used in Indian nuclear power plants. The demonstration of LBB based on fracture mechanics requires information on the initial size of a defect, initiation of crack growth from the inherent defect and subsequent crack growth rates. The crack will grow and penetrate the wall thickness under fatigue loading. Thereafter, the crack will grow in circumferential direction under cyclic loading. Therefore various tests are required for the deformation of fatigue crack initiation, fatigue crack growth, fatigue resistance behavior of the component. Fatigue crack initiation and crack growth rate of the actual piping component will also be useful in the accurate prediction of the remaining life prediction of the component, which is of concern to most of the old nuclear power plants.

(a) Fatigue life calculation

Fatigue life (N_f) , number of cycles to cause fatigue failure at specified stress level. Using crack growth laws it is possible to predict the life of pipe component subjected to fatigue under repeating load. The crack growth rate (da/dN) can be related to variation of stress intensity factor (ΔK). If ΔK remains constant Paris has expressed the relationship between crack growth (da/dN) and ΔK in the following form:

$$\frac{da}{dN}=C(\Delta K_d)^m$$

Where C and m are crack growth constants (Paris constant) depend upon the material and
ΔK= Kmax – Kmin. The Kmax and Kmin are stress intensity factor values corresponding to maximum and minimum stress level in the fatigue load cycle. [3]

For assumed initial crack depth, the no of cycle required for the incremental increase in crack depth can be calculated as follows.

$$dN = \frac{da}{C(\Delta K_d)^m}$$

ΔK_d = SIF range at deepest point of surface crack,
da = assumed increase in crack depth

Then extension in the crack length at the surface can be calculated from following equation by putting the number of cycles:

$$dc = dN * C(\Delta K_c)^m$$

Where dc = extension of crack length and
ΔK_c = SIF range of surface crack tip

The computation of crack propagation along two directions has to be carried out simultaneously, now new dimensions of crack geometry are calculated as

$$a_{new} = a_{old} + da$$
$$2C_{new} = 2C_{old} + dc$$

The process is repeated until the crack reaches through thickness or K reaches fracture toughness of the material for every incremental increase in a crack depth, the life cycle are calculated using equation

$$dN = \frac{da}{C(\Delta K_d)^m}$$

IV REVIEW

Few of the works have been summarized here done by various researchers, scientists, engineers and designers on crack growth behavior and fatigue fracture of pipes containing surface flaws under different loading conditions in nuclear power plants.

In 1968, Dr. James Rice first proposed the J-integral as an elastic-plastic fracture mechanics (EPFM) methodology. It provided the basis for EPFM fracture mechanics methodology well beyond the validity limits of Linear Elastic Fracture Mechanics (LEFM). Since then, this parameter has become the predominant method to characterize elastic-plastic fracture in the nuclear industry. The J integral has been used to characterize the crack driving force, crack tip stress field and the strain energy release rate during crack growth under elastic plastic. Thus the J integral can be viewed as both an energy parameter and a stress intensity parameter for non-linear materials.[3]

Kang in 2005 discussed the effects of stress amplitude and mean stress on ratcheting and failure under uniaxial asymmetrical stress cycling. It was concluded that the material apparently featured cyclic hardening; cyclic hardening depends greatly on strain amplitude. It was also observed that the ratcheting strain rate (i.e., the increment of ratcheting strain in each cycle) decreases gradually with the number of cycles due to its cyclic hardening feature.[4]

S. Vishnuvardhan studied on pressurized piping components of power plants were carried out on TP304 LN stainless steel straight pipes of 168 mm outer diameter subjected to steady internal pressure and four point cyclic bending. The length and average thickness of the pipes were 2800 mm and 15 mm respectively. The thickness was reduced to 12 mm in the gauge length portion of 200 mm at the centre of the pipe. Post-yield two element rosette strain gauges were mounted at various locations within the gauge length to measure the longitudinal and circumferential strains. The pipes were filled with water and pressurized; the pressure was maintained at 35 MPa till the first through-thickness crack was observed. Number of cycles corresponding to through-thickness crack/s and final failure of the component were recorded. Study give valuable inputs necessary for designing the components and assuring the integrity of pressure boundary under design basis loads such as loads arising during an earthquake event.[5]

Piping elbows are one of the critical components of the cooling piping system in power plant. Nagapadamaja P. et. al. presented the details of fatigue crack propagation analyses based on code procedure and FEM and compared the result with experimental observation. The fatigue crack propagation was evaluated based on in elastic range J-integral, J_s which was obtained by applying plastic correction (from RCC-MR code) to the elastic J-integral values from the code as well as from the elastic finite element analyses. The fatigue crack propagation was also studied directly using the elastic-plastic J-integral values obtained from finite element analyses. It was observed that the fatigue life calculated based on the modified J_s integral was close on the conservative side to the experiment results, then that from J-integral obtained directly from elastic-plastic finite element analyses[6].

The wall thinning that occurs due to erosion corrosion is exaggerated at elbows. Takahashi Koji et. al. conducted low-cycle fatigue test using elbow specimens with local wall thinning, which was machined inside the elbow in order to simulate metal loss from erosion corrosion. They did it in three different areas. Then the specimens were subjected to cyclic in-plane bending under displacement control without internal pressure. In addition they carried out 3-D elastic plastic analysis using FEM. The crack penetration area and the crack growth direction were successfully predicted by the analysis. The fatigue lives estimated by the analyses were close to those obtained by the experiment. They conducted whole experiment by STS410 (carbon steel pipe) in JIS (Japanese industrial standards), which are used in the class 2 piping of nuclear power plants in Japan. The software codes used in the analyses were Excel and Hyper Mesh for generating the FEM and element break down, ABACUS as the solver, and ABACUS VIEWER for post processing [7].

Dhakad S. K. et al. [3] presented fatigue crack growth behavior of surface cracked piping component were performed on the basis of LEFM principle with particular interest in its ability and accuracy, to predict full scale component tested experimental data. Especially the stress intensity factors available in literature were evaluated to predict growth behavior of the component using the specimen test material data. They concluded that the available SIF solution like ASM and Bergman for external surface crack straight pipes having the semi elliptical crack profile over predicts fatigue life of the component, when having constant crack depth profile in case of PBSE 8-3 pipe. Using Bergman solution the SIF results at the deepest point was higher as compared to solution of ASM handbook.[8]

Many studies were carried out at CSIR-SERC on nuclear power plant piping components subjected to monotonic as well as cyclic loading to assess the damage for crack growth due to low- cycle fatigue in circumferentially through wall crack pipes. Rohit et. al. worked on 304LN stainless steel piping components. They estimated J-integral for circumferentially TWC straight pipes subjected to monotonic and cyclic loading. They estimated monotonic J-integral by using Zahoor Kanninen approach, where as cyclic J-integral by using Dowling and Begley method [9].

The LBB concept has an effect on the safety design of fast breeder reactor (FBR) and thus into assessment has been one of the most significant issue. In the case of commercial scale FBR since the main loads are the thermal expansion to the thermal transient stresses, ferrite steel with a low-thermal expansion rate has been a candidate material. Moreover thin walled and large diametric pipes had been used to reduce the number of loops, which might also results in an economical advantage. Yeon-Sik Yoo et. al. proposed to apply the LBB assessment method to ferrite steel pipes with thin wall and large diameters [10].

3-D finite element analyses models were built for pipes with circumferentially cracked and the effect of thermal aging embrittlement on LBB behavior was analyzed by Chinese researchers Xunming LV et. al. they demonstrate that less conservative LBB assessment results will be produced, if thermal aging embrittlement and piping steel is not taken initial consideration. They chosen cost duplex stainless steel of Z3CN20-09M and the main ferrite content was 14.6%. They conducted that the fatigue crack propagation of surface cracks is less than 2% of the wall thickness during the entire life period also the un-aged and thermally aged pipes may fail with ductile fracture but thermal aging reduce the safety margins [11].

Extended Finite Element Mechanics (XFEM) is used to evaluate the SIF of a semi-elliptical part through thickness axial/circumferential crack by Kamal Sharma et. al. in his study [10]. They subjected internal pressure to pipe/pipe-bend having a crack on the outer surface. They found from these simulations that axial crack is more severe than the circumferential crack. They observed that the loading also significantly affect the SIF. These simulations also show that the modeling and simulations of cracks in XFEM is much easier as compared to FEM.[12]

After the accident at Fukushima Dai-ichi NPP in 2011, IAEA requires to consider the design extension conditions (DEC) for the safety management of NPP. Because piping systems are out of the components of NPP, and there is a possibility to failure at seismic events. So, Nakamura Izumi et. al. conducted an experiment investigation on failure modes and mechanisms of piping systems under excessive seismic loads. To clarify the failure modes under excessive seismic load, shaking table tests on different scale test specimens with different material or loading conditions were planned. They observed most of the failure modes were fatigue failure, other failure modes such as ratchet deformation, collapse and the fracture appeared under extreme conditions of fundamental plate tests. They used Carbon steel STS 410 as per JIS and stainless steel 304SS [13].

Sahu M. K. et. al. studied total three straight pipes which are used in primary heat transport system of Indian PHWRs (Pressurized heavy water reactor). Fracture tests had been performed on these pipes subjected to constant internal pressure and monotonically increasing four point bending load. Different experimental and finite element results like load vs load line displacement, load vs crack mouth opening displacement (CMOD), crack initiation loads are compared found in good agreement. Then they used experiment results for calculation of fracture toughness i.e. J-R curves for all three pipes. They observed higher J-R curve of surface crack pipe is attributed to prevalent lower crack tip constraint and vice-versa is true for through wall cracked pipes[14].

Dhakad S. K. et. al. Investigated, the fatigue crack growth behavior of surface cracked piping, pressurized base straight component (PBSC 8-5) on the basis of linear elastic fracture mechanics (LEFM) principles. Stress intensity factor available in the open literature were evaluated to predict the crack growth behavior of the component using specimen tested material data. They had concluded that the SIF solutions of ASM and Bergmann for external surface cracked straight pipe case having the semi-elliptical crack profile predicts the fatigue life of the component, when having constant crack depth profile. They also concluded that the initial crack size, aspect ratio of crack, applied bending stress range, stress ratio, diameter of pipe are some of the factors affecting the fatigue crack growth life of the piping component.[15]

Fatigue crack initiation and growth rate studied by Raghava G., in different exposure and loading conditions were carried out on twenty six straight pipes made of type 304LN stainless steel, which is widely used steel in nuclear power plant piping components. The pipe dimension were in two categories OD-170mm, thickness 15mm and OD-324mm, thickness-28mm. The specimen contained preexisting flaws in the form of part through notch in one of the following locations: base metal, heat affected zone and weld metal. Notch length varies from 7mm – 12mm and notch depth varies from 3mm – 10.9mm. twenty one specimen were tested under four point in air environment, there under four point in water environment, and two under combined torsion and bending in air environment [16].

V CONCLUSION

Numbers of researchers, scientists, engineers and designers have studied crack growth behavior and fatigue fracture of pipes containing surface flaws under different loading conditions in nuclear power plants. Few of them have been summarized above. Many kinds of softwares also been used by them, still scope for the search of reliable, easy to use and cost effective method is there. Which can incorporate all kinds of results in less time.

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