REVIEW ON VARIOUS PRACTICES ON FATIGUE ANALYSIS OF NUCLEAR POWER PLANT PIPING COMPONENTS

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ABSTRACT:- *There are many causes of fatigue failures in in-service condition, of piping components in nuclear power plants. But variable loading conditions are more liable, hence is discussed in this paper. Characteristics, causes and applications of fatigue crack growth in nuclear power plants were discussed and reviewed. This article reviews literatures which were summarized to understand factors influencing crack growth rate, current techniques and traditional methods of fatigue crack growth rate, data generation and their numerical analysis published since 19th century. Results from experimental studies, numerical analyses and computational datas via dissimilar sample geometries of pipes and loading situations are summarized and discussed.*

Keywords - ***NPP, FCG, LBB, J integral, SIF, FEM***

1. INTRODUCTION

Over last several years, various works have been done all through the globe to formulate a scheme oriented style for measurement of effect of fatigue in piping components of power plants. Piping components (pipes, elbows, joints), nozzles, valves and pumps in plants are structural components in a nuclear power plant (NPP) which are most prone to suffer from fatigue failures. Pipes and elbows are important components in piping systems. When elbow is subjected to variable loading, piping components are more liable to crack. The stress/strain concentrated at the internal and external surfaces of pipe-elbows at crown, intrados and extrados locations, which causes failures. The numbers of cycles of failures are not known in most of cases, but it has been assumed to be in the order of 10^7 cycles or more.

To assess remaining life for the duration of in-service procedure of components, this makes more logic to chase the plant operational record as it proceeds. To pursue this approach, it is extremely essential to process in addition to manage the plant in service datas like that they will be use for an exhaustive fatigue analysis. Computerized system software which can assemble these necessities, were available commercially and applied for various parts in usual nuclear power plants. Rewards of these computerized systems are (i) give numbers to report for real fatigue load

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(ii) Remaining life portion (iii) number of cycles for through wall crack (iv) additional trustworthy data base of piping system to apply for fatigue analyses for evaluation of damage mechanism or remaining life, together with ecological and load-history property. Hence, an add to in plant component presentation as well as better safety was anticipated.[1]

August Wohler (1860-1870) studied and discussed failure system of locomotive axles; by means of apply restricted load cycles and even given theory of stress-number of cycles (i.e. S-N diagram) to calculate fatigue life. Spurred complete investigation work on this theme was done after a serious accident which was take place just about 20th century. Fatigue is the principal mode of failure to be considered in the designing of components and different 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.[2]

Many experimental, numerical, analytical along with comparative study was done on pipes and pipe elbows having circumferential inner or outer surface cracks or through wall cracks to evaluate J-integral and collapse load. Works of a number of researchers have been summarized here to understand methods used to analysis of fatigue failure especially in pipe and piping components present in nuclear power plants.

2. PIPING MATERIAL USE IN POWER PLANTS

Common materials found in power plants are metals, properties of which are determined by size, composition and distribution of the crystal grains making up the microstructure.

The low alloy steels with manganese and chromium less than 5% weight obtained corrosion resistance. The stainless steels require chromium above 12% often with nickel and lesser amounts of molybdenum or niobium. A major application of nickel alloys in the nuclear power plants is the tubing of steam generators in reactors. For high temperature applications, nickel alloys were used. Molybdenum can be added for extra protection in very aggressive environments.

Zircaloys (about 1.5% by weight tin) have greatly use in the power plants in in-core structures, where its corrosion resistance makes it suitable for pressure tubing in water cooled systems.

Copper has important role for heat exchanger tubing due to its high thermal conductivity. The brasses, resulting from alloying with zinc are used extensively in cooling water systems and for condensers. Copper alloyed with nickel used for more corrosion resistant material. When copper must be avoided, titanium is recommended.

Finally, non-metals such as ceramics and polymers used as insulators, construction materials, heat exchanger tubes and machine parts.[3]

Xuming et. al. obtained that Z3CN20-09M steel was more susceptible to thermal aging, em-brittlement for longer service condition, ensuing in more tensile strength with noteworthy degradation of fracture hardiness of component. They observed that the consequence of thermal aging over growth performance of partial-through cracks is not noticeable. They also studied that the critical crack length which was considered by means of J-integral stability-assessment-diagram method, decrease with 13.55% while thermal aging was taken into consideration, however thermal aging decrease the component security limits.[4]

3. METHODS OF ANALYSIS OF CRACK GROWTH BEHAVIOUR

A. Experimental

In last few years, a large number of methods were used to calculate crack initiation, crack propagation and final fatigue life. Displacement gauge is generally mount on the opening of crack and a load displacement curve was drawn; variation in slope of curve provides a sign of crack opening along with closing. Many researchers also used electric potential drop and ultrasonic methods. The crack opening displacement (COD) method was considered to be superior on other methods.

Paris law [5] was based on crack propagation or crack- growth in single trend which is perpendicular to the bulk greatest principal stress axis.

Bhandari et. al. analyze crack initiation, crack shape and crack enlargement when crack located at crown position of pipe. Their specimen pipe was made of 304 stainless steel substance at in service temperature with sodium as fluid environment.[6]

E. Smith (1996) studied that hypothetical analyses for simple model of piping systems with an authentic circumferential crack which was provided with a seismic load, showed that the deformation at cracked section grow firstly by bending, after that internal loadings along with end-point displacement loading have been treated in the identical manner, as a result their special effect on crack propagation stability will be characterized.[7]

The effect of different temperature and sample direction, over the matter property has been described by P. K. Singh et. al.. Tensile strength and fracture property of SA 333 Gr6 steel as material were used in the PHT structure piping of an Indian PHWR. The piping specimens used was pipe and pipe elbow with outer diameters 219mm and 406 mm. J integral test also performed on the specimen made from the same carbon steel and welds of genuine PHT pipes. They also compared FCG curves (da/dN vs SIF) achieved from TPB specimens as mentioned in ASME section – XI. They observed LCF properties were superior at room temperature in contrast to 288^0 C meant for low strain array, while on high strain array fatigue curve of SA 333 Gr6 carbon steel pipe match up fine as given in ASME section - II of boiler in addition to other pressure vessel code for Carbon-Manganese steel. They accomplished to facilitate FCGR didn't depend on the notch direction, pipe dimension and their manufacturing procedure.[8]

Crack growth behavior in SA333 Gr6 steel pipe (applied in PHT piping arrangement of Indian PHWR with circumferential crack of huge aspect ratio of 20-50 have shown by Singh et. al.. Though, crack aspect ratio in addition to load combination was occurred when crack propagation will be taken place only in thickness direction. They use stress intensity factor (SIF) calculated at two positions that is at crack-tip ends and maximum depth.[9]

Cruse and Besuner proposed a powerful method that accounts an averaged root-mean-square with efficient stress intensity factor (K_{RMS}) at crack-tip end points and maximum depth, have been used for Fatigue Crack Growth (FCG) and total life forecast of components. It is a system that was not directly considered the outcome of 'K' value at various points along the crack front.[10]

Singh et. al. studied fatigue analysis on pipes and pipe elbow of carbon steel (SA333 Gr6). To analyse the behavior of crack growth with part through notch under seismic load for various pipe dimension, notch aspect ratios etc. They also compared fatigue crack growth rate curve acquired from three point bending sample pipe by ASME section-XI, which comes to be nearly the same.[11]

Hsua et. al. studied fatigue crack opening in compressive stress situation. They observed propagation of crack from internal surface at crown area which is taken place due to coalescence of numerous initiated cracks.[12]

Koji Takahashi et. al. investigated the low cycle LCF behavior of pipe elbow undergoing local wall thinning, located at crown, intrados and extrados. Pipe-elbow specimen was subjected to cyclic in-plane bending in displacement control lacking any inner pressure. They told, if thinning is situated at the intrados, the crack was beginning at the external surface of the intrados in addition to spreaded in the hoop direction. This behavior of pipe failure was unusual from the sound pipes. Fatigue life of pipes at intrados were shorter than that the sound pipes. But if local wall thinning was situated at the extrados or crown, the crack was started at the internal surface of crown and propagation in the longitudinal trend. Fatigue lives of extrados crown pipes were nearly identical to the ideal pipes. So, local wall thinning will not influence the LCF performance but if thinning is at extrados crown. Crack growth directions were successfully estimated by Finite Element (FE) analyses. They also concluded that the fatigue life evaluated by investigation was close to the fatigue life calculated experimentally.[13]

Punit Arora et. al studied FCG behavior of pipe weld and pipe elbow, which were sum up as two plans found to be evaluation of valuable SIF, results were slightly differ from fatigue life assumptions. Schemes based on K_{RMS} offer quite similar outcome with respect to experimental results whereas another scheme gives slightly conservative assumptions. Uses of Finite Element (FE) analysis and results from Paris Law have analogous calculations, till aspect ratio 0.6 for axial and circumferential crack orientations at extrados and intrados position respectively. Numerous openings of cracks were seen from inner surface of pipe in compressive stress state. Crack growth evaluations in compressive stress field desires various systematic approach.[14]

Xiang et. al.[15] presented experimental setup and three different techniques – EUC, normalization and DCPD for evaluating ductile fracture toughness in metals using the J-R curves. The J-integral evaluations were same in all three methods, with differences primarily involving crack size measurements. EUC relies on material compliance to device the real time crack size, while for the normalization method, primary and ultimate crack lengths were calculated and intermediate crack sizes are determined based on the normalization function. For DCPD, the correlation between potential drop and crack size is exploited to assess crack size. All three methods are applicable for testing in the normal temperature range. However, for elevated temperature tests, the material relaxation behavior and increased friction between the loading clevises and pins degrade the accuracy of the elastic compliance measurements for the EUC method, so normalization or DCPD would be used. In addition to this the original J-R curve based on DCPD requires adjustment to account for the deformation-induced potential drop.

M. K. Sahu et.al. studied on three pipe specimens which were applied in PHT system of Indian PHWRs. Fracture analysis was carried out with these specimen pipes which were focused to invariable inner pressure which then monotonically rising to four point bending load. various investigational and finite element (FE) outcomes similar to load vs crack mouth opening displacement (CMOD), load vs load line displacement, crack initiation loads which were match up to and bring into being in quite high-quality accord. J-R curves were drawn for every pipe specimens by considering experimental outcomes of load, load line displacement and crack growth rate datas. J-R curve was set up to be appreciably superior, obtained for surface cracked pipe as compared to through wall cracked pipes. These J-R curves for Triple Point Bending sample with both through wall cracked pipes were obtain to be on same levels.[16]

B. Leak Before Break (LBB)

There are several steps in J. Chattopadhyay et. al. work of Leak Before Break condition namely- assessment of load for piping structures, creation of fracture and tensile properties of Primary Heat Treatment pipe base as well as welded materials, calculation of leakage crack size and EPFM and limit loads respectively. They studied the fatigue-fracture examination of straight pipes with pipe elbows used in PHT system of TAPP 3 and 4. [17]

Y. S. Yoo and Ando[18] studied LBB behavior on pipe having circumferential crack subjected to cyclic loading in comparison of Leak Before Break situation among static in addition to cyclic loading. They accomplished that Leak Before Break behavior was more expected to occur in statistically vague piping system, like decline of ultimate strength suitable to adequate rearrangement of bending moment within there scheme was moderately less.

C. Finite Element Method (FEM)

Few typical crack troubles have stopped from critical result. So, mathematical methods were the option to analyze cracks inside pipes and pipe bends under diversified kinds of loads. To analyse semi-elliptical cracks located over the external surface of spherical pipe and its bends, finite element method have been developed by Henshell and Shaw in (1975) and Akin (1976). FEM is the numerical methods to obtain approximate solution to many fracture mechanics problems. For these problems boundary element technique developed by Portela et. al. in 1991 and mesh free techniques in 1994 by Belytschko et. al. In Finite element process, geometry has been model by sufficient mesh, as crack features must be equivalent through the frame of finite elements.

Saxena et. al described to utilise 3-Dimensional non-linear Finite Element Analysis supported with investigational findings to find out collapse limit load. Analyses were executed, taking into account equally material with geometrical non-linearity by means of highly developed fracture study code WARP3D. They presented that both investigational and FEM model outcomes be incorporated to facilitate the FEM simulation predicts experimental results were sensibly good.[19]

Fatigue analyses using 3D modeling for the fatigue damaged components were performed to extend the optimized fatigue system by Taesoon Kim for chemical volume and control system (CVCS) charge inlet nozzle of the power reactor components.[20] Collective fatigue usage factors considered by the detailed fatigue process found to be lower values than the reference values.

D. Linear Elastic Fracture Mechanics (LEFM)

S. K. Dhakad et. al. investigated fatigue crack growth (FCG) actions in surface crack pipe components were executed at the beginning of LEFM. They accomplished that the existing SIF solutions similar to ASM and Bergman in favor of surface crack pipe having semi-elliptical crack sketch over predict fatigue life of section after having regular crack depth sketch. They showed that in case of Pressure based straight component PBSC 8-3 pipe, Bergman clarification for the SIF results at the deepest point is higher as compare to relevant solution of ASM handbook. Bergman solution predicts inferior values of surface SIF as compare to ASM solution. When they compared the results with their experimental results they found that for the particulate case both SIF solutions over calculate fatigue life of the element. ASM SIF solutions give higher over prediction (184.7%) of the fatigue failure life as compare to that predicted by Bergman SIF solutions (154.5%). The increase in crack length predicted by Bergman solution compare well (0.16%) with experimental results and is also better than that of the predicted values by using ASM SIF results (3.6% over prediction).[21]

S. K. Dhakad et. al. performed fatigue crack development behavior of surface crack pipe, PBSC 8-5, on the base of the LEFM principles. They concluded that SIF solutions forecast the fatigue failure lives of pipe components, in case of pipe 8-5; here Bergman has given improved results. The predicted outcomes were initial crack opening size, aspect ratio of the crack, functional bending stress range and stress ratio, diameter of pipes were several factors disturbing fatigue failure lives of piping components.[22]

E. Extended Finite Element Method (XFEM)

This is a modern and most effective method, in which a new element is introduced, at the fracture tip and outside the fracture tip, conventional element were placed. Gifford and Hilton was introduced this and it gives more accurate results than conventional method.[24] Now all FEM based programs like Abaqus and ANSYS etc. also accepted this method and worldwide research and industrial filed this method is widely accepted.[23]

During XFEM, partition of unity method was applied for the enhancement of displacement estimation by means of supplementary functions (Modes et. al.). These enhancement functions were obtained as of the hypothetical conditions of the trouble in concern. Numerous enhancement functions were projected through researchers like Sukumar et. al., 2001 to model cracks in XFEM. Mainly two enhancement functions were essential to produce crack in XFEM; one was not continuous on the crack surface and second was asymptotic on crack front. As a result, XFEM provide specific modeling of cracks.

Kamal et al. used XFEM to estimate the SIF at semi-elliptical fraction in the course of thickness axial/circumferential crack present on each at extrados and intrados on pipes and pipe bends falling under interior pressure or opening bending moment. To improve displacement estimation by means of additional functions, partition of unity method will be considered. To precisely replicate a crack, level set function was estimated via superior order shape functions. Domain based interaction integral method was applied to find out SIF's by XFEM results. Six dissimilar cases of circumferential and axial cracks were replicated. Then they compare their findings obtained by XFEM method with the FEM results. Findings showed that the position of crack and loading have considerable effect on their Stress Intensity Factors. All these findings will demonstrate that modeling in addition to simulation of cracks by XFEM will be quite easy as compared to FEM.[25]

F. Stress Intensity Factor (SIF)

A distinctive piping system comprises of arrangement of pipes and different fitting components. The nuclear power plant piping systems are subjected to many type of loading due to load, temperature, pressure, wind, vibration etc. resulting in various failure modes. Also, pipe exhibit various geometric distinctiveness at fittings which effects on flexibility of piping systems, which influences stress concentration at fittings.

SIF has been calculated by:

$$K = Y \times \sigma \times (\pi a)^{1/2}$$

Here Y is function which is dependant on geometry of crack and cracked fraction in concern, σ is the nominal stress acting normal to the crack and a is size of crack. If SIF exceed its upper material limiting value, the crack propagation is uneven which causes failure of the component. But if SIF was lesser than the threshold value, crack propagation will not be predictable. [26]

Gaurav et. al. had few comments on B31 SIF equations and hence attempt to compare results of B31 SIF results adjacent to finite element (FE) analysis provided the results at the end. They observed that SIF for the same component can be dissimilar in different codes. B31 SIF decrease as pipe diameter decreases. Finite element analysis indicates that as pipe head diameter decreases, head SIFs decreases and branch in-plane SIF also decreases, out-plane SIF initially decreases and then show increasing tendency. In common, B31 equations offer conservative values of SIF compared to FEA. Therefore, in case of critical systems detailed study is mandatory prior to adapting any SIF value.[27]

F**. J integral**

During late 1960s, J-integral was projected to illustrate stress-strain just about the crack tip to an elastic-plastic material by J. R. Rice. Via idealizing elastic-plastic deformation the same as non-linear elastic deformation, He provides base for broadening fracture mechanics well ahead of validity limits of LEFM. Experimental assessment requisite a large number of component samples of various crack lengths to calculate J-integral. Rice proved that non-linear energy release rate might be measured by considering a line integral termed as J integral, which is calculated with the random contour around the crack-tip. He showed the path independent J-integral for linear and for non-linear elastic materials by means of deformation hypothesis for plasticity that eliminates concern of unloading. Rice et. al. (1973) proposed η_{pl} (function to product area under load against load-point-deflection curve) to estimate J-integral. This scheme requires less number of specimens to calculate J-integral. Rice proposed the value of η = 2 designed for severely cracked or bend sample. They anticipated dividing entire J-integral into plastic (J_p) and elastic (J_e) fractions, i.e. $J = J_p + J_e$. [28] [29]

Dowling and Begley prepared an attempt to use J-integral theory like an elastic-plastic measure for FCG. Experiments engaged compact tension (CT) samples for pressure vessel pipes prepared of A533B steel material.[30]

Hutchinson and Paris carry out investigation with the purpose of outer surface for the core of non-proportional loading so that bend was almost comparative. Given the region of non-proportional loading has been found controlled in the area conquered through the J-singularity, here an annular area wherever HRR field holds. But if a sample's un-cracked segment is adequately huge in contrast to the central core of non-proportional loading in addition to the J-stress field conquered crack expansion, the crack propagation might be restricted by means of J-integral.[31]

Merkle with Corten anticipated η function intended for compact tension (CT) sample acceptable to the bending load with tensile load. After that, Ernst et. al. even more simplify CT process and formulated the 'γ' function for CT and TPB samples.

They have publicized that at all times exist if a separation of variables can be establish for loads in terms of crack length and plastic load-line displacement. It was demonstrated by sketching load against plastic load-line-displacement curve for a variety of constant values.[32]

Zahoor and Kanninen anticipated a technique to estimate J-integral for a circumferentially crack pipe component in bending that proof feasible assessment of a J-R curve straight as of the load displacement documentation acquired in pipe fracture test. They too allowed an investigation for fracture volatility for circumferential crack propagation by means of a J-R curve and tearing modulus factor. On the other hand, in order to create sensible prophecy for firm crack growth and volatility, appropriate J-R curve fulfilling limitations at the crack tip will be used. [33]

Roose et. al. planned limit-load based universal term, plastic η feature, for investigational measurement for plastic J-integral of fracture mechanics samples. They derived the η_{pl} functions for various specimens.[34]

Researches were furthermore made by Rahman and Brust where method has been projected to guess J-integral with COD of TWC pipe weldment subjected to out-of-the-way bending load. Closed figure solution was acquired in expressions of basic functions for fairly accurate estimation of energy release rate and core COD. [35]

Miura et. al. derived the η_{pl} and γ η_{pl} functions from measurement examination to estimate J-R curves meant for pipes among through-wall circumferential crack underneath collective bending and axial tension. They would not incorporated expressions related for broad pipes. [36]

J. Chattopadhyay et. al. (2001) concluded that limit load-based universal term of γ was derived. Where γ is the expression to rectify the J-integral in the direction of report for crack propagation, which will be certified by obtaining the η_{pl} and γ expression for different geometries, they consist of triple point bending specimen, a through wall circumferentially crack pipe in four point bending load and axial tension. They conducted tests on 200mm thick elbows with through wall circumferential cracks having in-plane bending moment. The η_{pl} and γ expressions for different geometry which will be utilized to assemble the element of J-R curves.[37]

Cho et. al. explained better assessment of J-integral for pipes having circumferential semi-elliptical crack subject to internal pressure, tensile loading and total bending. Approaches were agreed in two dissimilar types to cover up variable dimensions and material properties; a customized GE/EPRI process and a customized suggestion stress process was authenticated over consequent thorough elastic-plastic FE studies by taking real material statistics of usual stainless steels.[38]

Rohit et. al. in 2012 expected J integral for circumferentially through wall crack straight pipes intended to monotonic repeated loading. Monotonic J integral was expected by means of the approach specific by Zahoor and Kanninen, while repeated J-integrals were expected with process anticipated by Dowling and Begley. Monotonic J-R curves were obtained, a quadratic polynomial be fixed with J-R curve with an expression between J and Δa has been acquired. In the same way they obtained returning J-R curve and da/dN vs. ΔJ curves. [39]

4. CONCLUSION

Analysis shows that fatigue life has been consider of being self-possessed of three different segments: crack initiation, crack growth/propagation and ultimate failure of sample components. General conclusion is that the circumstances in which a variety of phenomenon can influence changeable amplitude fatigue crack growth and relations between them are insufficiently documented. A large number of observed fatigue crack growth laws have been anticipated for numerous materials through experiments, arithmetical and analytical methods like finite element analyses. This has been observed that XFEM is the best approach to analyze a crack growth. Different fatigue analysis softwares already adapted XFEM like ANSYS, ABAQUS etc.

5. REFERENCES

1. J. Jansky, H. Schulz, "Comments on the present practice of fatigue analysis of nuclear power plant components", international journal of pressure vessels and piping, 34 (1-5), 1988, 143-154.
2. Bergman M., "stress intensity factors for circumferential surface cracks in pipes", Int. Frac. Engg. Mat. Struct., vol. 18, issue 10, 1995, 1155-1172.
3. Lister D. H., "power plants materials", thermal power plants- vol. I

4. Xuming Lv, Shilei Li, Xitao Wang, Yanli Wang, Zhaoxi Wang, Fei Xue, Hailong Zhang, "effect of thermal aging on the leak-before-break analysis of nuclear primary pipes", Nuclear engineering and design, 280, 2014, 493-500.
5. P. Paris and F. Erdogen, "A critical analysis of crack propagation laws", Journal of Basic Engineering, Transactions of the American Society of Mechanical Engineers, December 1963, 528-534.
6. S. Bhandari, M. Fortmann, L. Grueter, J. Heliot, P. Meyer, B. Precie du sert, A. Prado and H. Zeibig, "Crack propagation in a LMFBR Elbow", Nuclear Engineering and Design, 91, 1986, 107-119.
7. E. Smith, "Effect of intertial loadings on the criterion for stable growth of a crack in a piping system", international journal of pressre vessel and piping, 67, 1996, 119-125.
8. Singh P. K., Chattopadhyay K., Kushwaha H. S., Tarafdar S., Rangnathan V., "Tensile and fracture properties evaluation of PHT system piping material of PHWR", Int. J. of pressure Vessel and piping, 75, 1998, 271-280.
9. P. K. Singh, K. K. Vaze, V. Bhasin, H. S. Kushwaha, P. Gandhi, D. S. Ramachandra Murthy, "Crack initiation and growth behavior of circumferentially cracked pipes under cyclic and monotonic loading", Int J Pressure Vessel Piping, 2003, 629-640.
10. T. A. Cruse, P. M. Besuner, 12(4), pages 369-375, 1975.
11. Singh P. K., Bhasin, Vaze K. K., Ghosh A. K., Kushwaha, Ramachandra Murthy D. S., Gandhi P. and Shiv Prasad, "Fatigue studies on carbon steel piping materials and components: Indian PHWRS, Nucl. Engg. Design, 238, 2008, 801-813.
12. Tzu-Yin (Jean) Hsua, Zhirui Wanga, "Fatigue crack initiation at notch root under compressive cyclic loading", Proceedia Engineering, vol. 2, 2010, 91-100.
13. Koji Takahashi, Santoshi Tsunoi, Takumi Hara, Tomohiro Ueno, Akira Mikami, Hajime Takada, Kotoji Ando, Masaki Shiratori, "Experimental study of low-cycle fatigue of pipe elbows with local wall thinning and life estimation using finite element analysis", international journal of pressre vessels and piping, 87, 2010, 211-219.
14. Punit Arora, P. K. Singh, V. Bhasin, K. K. Vaze, D. M. Pukazhendhi, P. Gandhi, G Raghava, "Fatigue crack growth behavior in pipes abd elbows of carbon steel and stainless steel materials", procedia Engineering, 55, 2013, 703-709.
15. Xiang (Frank) Chen randy K. Nanstad, Mikhail A. Sokolov Eric T., "Determining Ductile fracture toughness in metals", advanced materials & processes, 2014, 19-23.
16. M. K. Sahu, J. Chattopadhyay, B. K. Dutta, "Fracture studies of straight pipes subjected to internal pressure and bending moment", international journal of pressure vessels and piping, vol.134, 2015, 56-71.
17. J. Chattopadhyay, B. K. Dutta, H. S. Kushwaha, "Leak-before-break qualification of primary heat transport piping of 500 MWe Tarapur atomic power plant", international journal of pressure vessels and piping,vol. 76, 1999, 221-243.
18. Y. S. Yoo and K. Ando, "Leak-before-break behavior of statistically indeterminate piping system", Nuclear Engineering and Design, vol. 224, issue 3, 2003, 253-263.
19. Sanjeev Saxena, N. Ramakrishnan, "Characterization of plastic collapse load determination in circumferentially through-wall cracked elbows", Nuclear Engineering and Design, 236, 2006, 1739-1747.
20. Taesoon Kim, Chankook Moon and Byongsup Kim, "Development of the 3D fatigue analysis procedure for major components of the new advanced power reactor", Transactions, SMIRT 19, Toronto, paper S02/3, 2007.
21. Shrikrishan Dhakad, Sanjeev Saxen and Geeta Agnihotri, "Fatigue crack growth and life prediction analysis of power plant component using LEFM approach", international J. of Multidispl. Research and Advcs. In Engg.(IJMRAE), Vol. 4(II), 2012, 131-140.
22. S.K. Dhakad, Sanjeev Saxena, Geeta Agnihotri, "Fatigue failure and life estimation analysis of straight pipe component using LEFM approach", international journal of mechanical and production engineering, vol. 4, issue 10, 2016, 114-117.
23. Nirpesh Vikram, Raghuvir Kumar, "Review on fatigue-crack growth and finite Element method", international Journal of Scientific and Engineering Research, Vol. 4, issue 4, 2013, 833-843.
24. Gifford, Jr. L. N. and Hilton P. D., "Stress intensity factors by enriched finite elements", Engineering Fracture Mechanics, vol. 10, 1978, 496-507.
25. Kamal Sharma, I. V. Singh, B. K. Mishra, V. Bhasin, "Numerical modeling of part-through cracks in pipe and pipe bend using XFEM", Procedia Materials Science, 6, 2014, 72-79.
26. Sanjeev Saxena, "Fatigue analysis of structures", fatigue and fracture behavior of components and structures, 4.1-4.37.
27. Gaurav Bhende, Girish Tembhare, "Stress intensification and flexibility in pipe stress analysis", international journal of modern engineering research (IJMER), vol. 3, issue 3, 2013, 1324-1329.
28. Rice J. R., "A path-independent integral and the approximate analysis of strain concentrations by notches and cracks", J. Applied Mechanics, vol. 3, 1968, 379-386.

29. Rice J. R., Paris P. C., Merkle J. G., "Some further results of integral analysis and estimates, In: Progress in flaw growth and fracture toughness testing", ADTM STP 536, Philadelphia: American Society for Testing and Materials, 1973, pp. 231-245.
30. N.E. Dowling and J. A. Begley, "Fatigue crack growth during gross plasticity and the J-integral", Mechanics of crack growth, ASTM STP 590, American Society for testing and materials, Philadelphia, 1976, 82-105.
31. J. W. Hutchinson and P. C. Paris, "Stability analysis of J-controlled crack-growtg", Elastic-Plastic fracture, ASTM STP 668, J. D. Landes, J. A. Begley and G. A. Clarke, Ed. American Society for testing and materials, 1979, 37-64.
32. Ernst H. A., Paris P. C., Landes J. D., " Estimation of J-integral and tearing modulus T from a single specimen test record", Fracture mechanics: 13th conference, ASTM STP 743, 1981, 476-502.
33. A Zahoor and M. F. Kanninen, "A plastic fracture mechanics prediction of fracture instability in a circmferentially cracked pipe in bending-part I: J-integral Analysis", J. Pressure Vessel Technology, 103(4), 1981, 352-358.
34. Roose E., Eisele U., Silcher H., " A procedure for the experimental assessment of the J-integral by means of specimens of different geometries", International Journal Pressure vessels Piping, 23, 1986, pp. 81-93.
35. S. Rahman and F. Brust, "Elastic plastic fracture of circumferentially through wall cracked pipe welds subject to bending", Transactions of ASME, 114, 1992, 410-416.
36. Miura N., Wilkowski G. M., "J-R curves from circumferentially through-wall cracked pipe tests subjected to combined bending and tension- Part II, Experimental and analytical validation", J Pres Ves Technol, Trabs, Am Soc Mech Engrs, 1998, pp.412-417.
37. J. Chatopadhyay, B. K. Dutta, H. S. Kushwaha, "Derivation 'γ' parameter from limit load expression of cracked component to evaluate J-R curve", international journal of pressure vessels and piping, 78, 2001, pp. 401-427.
38. D. H. Cho, H. B. Seo, Y. J. Kim, Y. S. Chang, M. J. Jhung and Y. h. Choi, "Advances in J-integral estimation of circumferentially surface cracked pipes", Fatigue and Fracture of Engineering Materials and structures, 34(9), 2011, pp. 667-681.
39. Rohit, S. Vishnuvardhan, P. Gandhi and Nagesh R. Iyer, "Monotonic and cyclic J-integral estimation for through-wall cracked straight pipes", international journal of civil, environmental, structural, construction and architectural engineering, Vol. 6, No. 8, 2012, 686-692.