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Research Article

Fatigue Life Assessment of Petroleum Pipe Elbows

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Abstract

Pipe elbows are important components in piping systems. When a thin-walled elbow is subjected to variable amplitude loadings (VAL) as internal repeatable or random load pressure, piping elbows are vulnerable to crack. The strain concentrated at the inner and outer surfaces of the elbow pipe for the locations at crown, intrados and extrados. The finite element analysis with the nonlinear kinematic hardening model has been used to evaluate the behavior of the piping elbows under Low Cycle Fatigue (LCF) condition for all the loading ranges considered. This analysis program included monotonic and cyclic loading systems. For this purpose, the finite elements analysis was being used for the modeling and simulation based fatigue analysis code procedure. Different elbows show the fatigue life behavior based on different locations. The simulation results showed that more studies on the piping elbows need to be perfumed in order to obtain more accurate fatigue life.

Keywords*: Fatigue life; Finite element analysis; Pipe elbow; Variable amplitude loading*

Introduction

Piping elbows are of the critical components of the piping systems in all applications. With an objective of understanding the cyclic fracture, fatigue crack growth (FCG) and behavior of steel piping components subjected to various operational. Integrity assessment of piping components is very essential for safe and reliable operations. Over the last several decades, considerable work has been done throughout the world to develop a system oriented methodology for integrity assessment of pipes and elbows. Pipe bends or elbows are commonly used as components in piping systems. It is important to know its limit load for the safe operation of the plant. Steel pipe elbows are essential components of industrial piping systems and steel pipelines, and their structural performance may be critical for the integrity of the industrial facility or the pipeline [Suzuki 2006, Prabhakaran and Venkat 2002].

Elastic-plastic fracture analysis of piping is increasingly important in life and structural integrity assessment [Diem *et. al.* 1989]. Significant efforts in developing fracture mechanics methodology have been made during the last three decades together with validation against finite element results and experimental pipe test data [Nagapadmaja *et. al.* 2008]. Accurate stress analyses of these components are required for reliable prediction of strength and residual life [Chattopadhyay *et. al.* 1999, Kim *et. al.* 2008]. Experimental and analytical studies were performed on straight pipes of different diameters and made of different materials to provide the data for leak before break criteria [Takahashi 2002, Venu Kumar *et. al.* 2002]. Analytical solutions are available for only a few idealized geometries. When a thin-walled elbow is subjected to an in-plane moment, vocalization of the circular section into an elliptical one, introduces high bending stress (circumferential components) at the crown and a crack may initiate at the crown. This has been confirmed by analytical and experimental work [Kano *et. al.* 1997, Muller and Diem 1985]. It was noticed during an experiment by Naoki [Naoki and Yasunari 1997] that, for a stainless steel elbow with an axially through-wall crown crack, the crack opened at the outside surface and contacted at the inside surface, when subjected to in-plane closing bending moment. Experimental, analytical and numerical studies were also carried out on elbows with circumferential surface cracks, internal and external meridinal surface cracks, external meridinal through wall cracks in elbows to develop J-estimation and to evaluate collapse load [Bhandari *et. al.* 2008, George and Varelies 2014, Kilinski *et. al.* 1996]. Stable crack extensions were observed in all the tests [George *et. al.* 2012].

The nonlinear kinematic hardening model is used to study the ratcheting behavior of stainless steel piping elbows under conditions of steady internal pressure and dynamic out-of-plane bending at frequencies typical of seismic excitations [Zakavi and Nourbakhsh 2014]. Degrassi *et. al.* [2003] performed based on seismic time-history finite element analysis of piping system for simulating responses, using bilinear, multilinear in ANSYS. Balan and Redektop [2004] simulated the response of elbow specimen under cyclic bending and internal pressure with bilinear plasticity model in the finite element code ADINA. More recently, Raham and Hassan [2009] presented an extensive analytical work on cyclic behavior of steel elbows. The behavior of steel pipe elbows subjected to strong cyclic in-plane loading has been studied experimentally. For arbitrary geometries, exact solutions are not available because of the complex nature of stresses and crack propagation at surface cracks in each case.

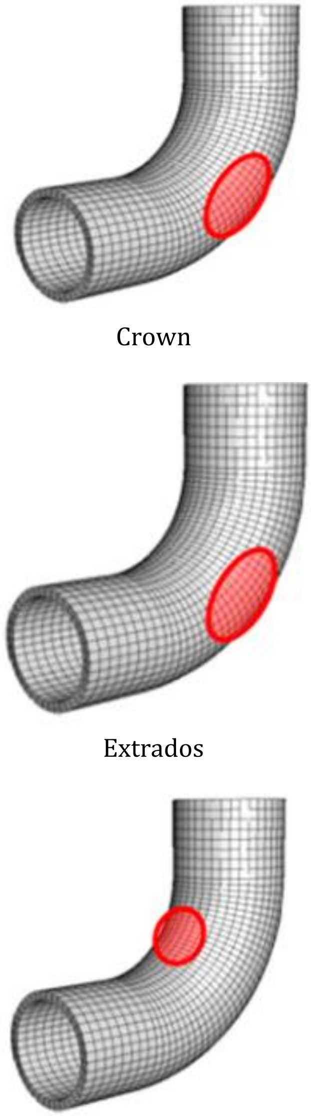
Some researchers have studied static and fatigue strength of elbows with local wall thinning [Kim *et. al.* 2008, Ahn *et. al.* 2002]. However, the low cycle fatigue strength of elbows with local wall thinning is not yet clear. The number of experiments on this topic is limited because they are expensive, laborious, and time consuming. It is preferable to establish an analytical approach to simulate the experimental procedure [Koji *et. al.* 2010].

In this paper, to study the fatigue life of elbows based on the strain-concentrated point occurred at the inner and outer surfaces of the elbow pipe for the locations at crown, intrados and extrados. For this reason this paper presents a technique to predict the fatigue life of elbows with the application of VAL for those locations. FEA of pipes elbows was carried out based on Glyphwork n-code software [Klyphwork 2003] and the full pipe elbow was modeled using tetrahedral element (Tet10). A fatigue life analysis based on the strain life approach was followed to obtain an estimate of the expected life of elbows, with application of monotonic and cyclic loading. It was observed that, in these pressurized elbows, cracks initiate at the inner surface of elbows. This implies that, for fatigue-life calculations, stress/strain data was required at the surface. From tests these data could be obtained at the outer surface only, since it was difficult to measure strain on inner side under pressurized condition. The other alternate, to obtain stress/strain data on inner side is to perform FEA analysis of these tests. Thus, detailed three dimensions, non-linear FEA of these accumulated tests under cyclic displacement controlled loading were performed.

Methodology

Piping systems are used in nearly every industrial facility in the world. Generally they are used to transport materials at a verity of pressures and temperatures. One of the most important components in these systems is elbows. They are added to the system to turn corners and to add flexibility to the network. By adding flexibility they are able to decrease the loads transmitted to base fixtures due to thermal and mechanical effects.

Historically, elbows have been difficult to analyze accurately. This uncertainly has led to the large safety margins seen in design codes. With the development of the finite element method of analysis it has become possible to model the behavior of the elbows using a variety of elements. Fig. 1 shows the finite elements model of elbow pipe at crown, intrados and extrados.



Crown

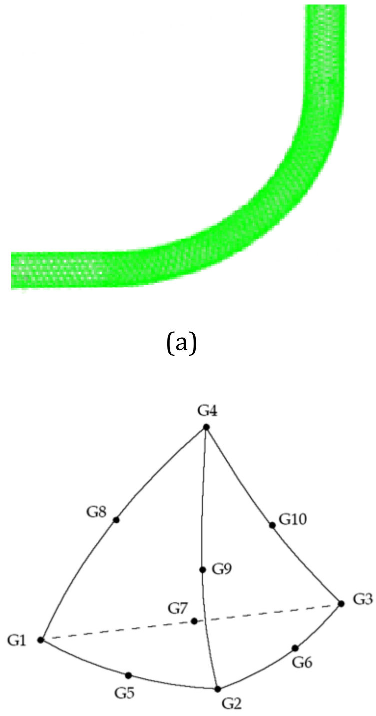
Extrados

Intrados

Figure1: Finite element models of elbow pipe at different locations

In comparison to other components of piping system, elbow is more flexible component and it leads to large deformation. Therefore, for the FEA of elbows, a fine meshed model is required. Generally the elbow is modeled as uniformly thick and leads to considerable ease in modeling. But in actual elbow, its thickness varies along axial as well as circumferential direction [Sumit *et. al.* 2011].

The finite element technique was used for modeling and simulation of the case study in three dimensions mesh shown in Fig. 2a. For this purpose, the FEA technique was being used for the modeling and simulation based on Glyphwork n-code analysis [Klyphwork 2003]. Selecting the right techniques of meshing is based on the geometry, model topology, analysis objectives and engineering judgment. The auto TetMesh approach is highly automated technique for meshing solid regions of the geometry. The type of elements used here was tetrahedral element (10 nodes) shown in Fig. 2b. The number of elements and nodes were 34257 and 68723 respectively.



(a)

(b)

Figure 2: (a) The three dimensions mesh elbow; (b) The tetrahedral element nodes

Components, structures are subjected to quite diverse load histories, their histories may be rather simple and repetitive, at the other extreme, and they may be completely random. Among these, two curves monotonic and cyclic that are LCF were used. The loading was continued for complete 20 cycles and the value of the internal pressure reach to 38 MPa. In this paper, the nonlinear kinematic hardening model is used to study the behavior of steel piping elbows. The linear and nonlinear kinematic hardening models were first proposed by Prager [1956] and Armstrong-Frederick [1966] respectively. The kinematic hardening plasticity models are proposed to model the inelastic behavior of materials that are subjected to repeated loading**.** The nonlinearities are given as a recall term in the Prager rule [1956]:

$$dX = \frac{2}{3} C d\varepsilon^p - \gamma X d\varepsilon_p$$

where X is the back stress tensor, $d\varepsilon_p$ is the equivalent plastic strain rate, C and γ are two material dependent coefficients in the Armstrong–Frederick kinematic hardening model, and γ = 0 stands for the linear kinematic rule. The evolution equation of hardening can be integrated analytically to give [Lemaitre and Chaboche 1995, Zakavi and Nourbakhsh 2014]:

$$X = \nu \frac{c}{\gamma} + \left[X_o - \nu \frac{c}{\gamma}\right] \exp[-\nu\gamma(\varepsilon_p - \varepsilon_{po})]$$

where ν = ±1 according to the direction of flow, and ε_{po} and X_o are the initial values, for example at the beginning of each plastic flow.

In this analysis, the material ASTM A533 steel has been used, for which the chemical compositions, mechanical properties and cyclic properties of the material at room temperature are listed in tables 1,2 and 3 respectively [Metals Handbook 1990, SAE 1999].

Table 1 Chemical composition (wt%) of the material

C	Mn	P	S	Si	Mo	Ni
0.170	1.390	0.003	0.013	0.250	0.460	0.590
Co	V	Al	Cu	Cr	N	Fe
0.007	0.003	0.026	0.005	0.004	36 Ppm	Bala.

Table 2 Mechanical properties of the material

Yield Strength (MPa)	Ultimate Strength (MPa)	Modulus of Elasticity (MPa)
670	720	205
Hardness (BHN)	Elongation (%)	
230	28	

Table 3 Cyclic properties of the material

Fatigue strength coefficient	*SF'*	975.3
Fatigue strength exponent	*b*	-0.095
Fatigue ductility exponent	*c*	-0.69
Fatigue ductility coefficient	*Ef'*	0.35
Cyclic strain-hardening exponent	*n'*	0.11
Cyclic strength coefficient	*K'*	940.2

Results and Discussions

The flexibility of elbows derives from their unique geometry. During deformation the cross section undergoes ovalization wherein the shape of the cross section tends to flatten. Depending upon whether the elbow is opening or closing, this can either stiffen or weaken the component. This process also leads to very high strain concentration in the mid-section of the elbow where failure becomes likely at high loads. Because of this occurrence, elbows are very important to the integrity of the piping network during severe loading events.

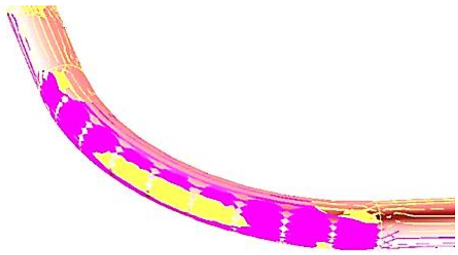


Figure 3: Contour display of strains in elbow

The results of the maximum principle strains are used for the subsequent fatigue life analysis. Fig. 3 shows the contour (image) of the strains distribution (maximum principle strains) on one of the elbows for Tet10 mesh elements at high load level.

It is known that under cyclic loading material undergo cyclic softening/hardening. This leads to change in stress-strain response cycle-by-cycle. Such model is not available in literature. Therefore, to simulate response of the fatigue test on elbow, various models were used in FEA. The loading was continued for complete 20 cycles. After each of the actual loading history the magnitude of displacement loading cycle in closing, followed by the magnitude of displacement loading cycle in opening were accounting.

Figs. 4 and 5 show the comparison of hoop strains based on two load models (monotonic and cyclic) at outer diameter (OD) and inner diameter (ID) for the three locations (intrados, extrados and crown). From these curves, it can be seen that, the accumulative of hoop strains are highest at crown location compare to intrados and extrados locations. Hoop strains at crown are 76% and 18% higher than intrados and extrados for OD cases respectively, while for ID are 10% and 3%.

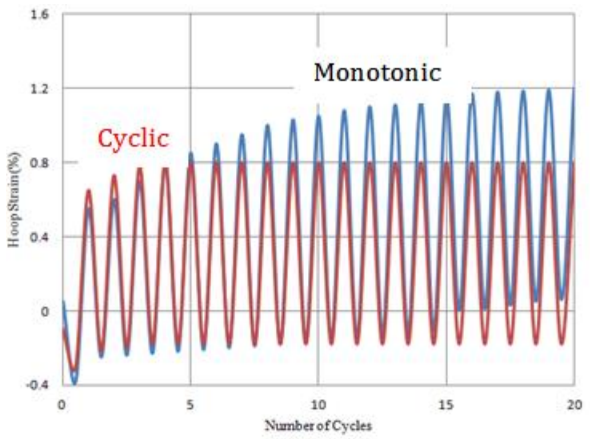


Figure 4a: Hoop Strain at Intrados OD

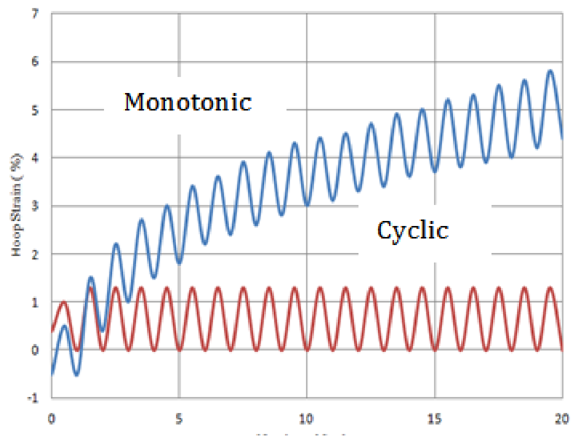


Figure 4b: Hoop Strain at Extrados OD

This indicate that in most of the cases the failure or the crack initiation will be near to the crown location, which is in a good agreement compared to the previous work [Suzuki 2006]. Fig. 6 [Sumit *et. al.* 2010], show the typical response of accumulated ratcheting strain versus number of cycles at crown, intrados and extrados. It is clear figure 6 that crown and intrados locations show continuous ratcheting.

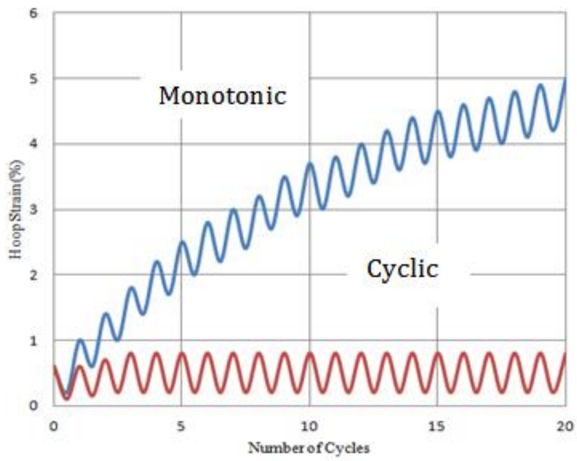


Figure 4c: Hoop Strain at Crown OD

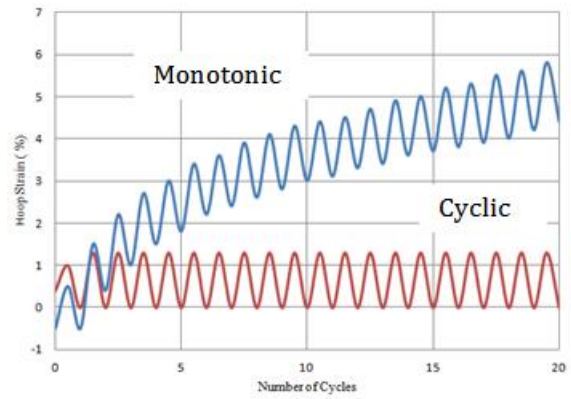


Figure 5a: Hoop Strain at Intrados ID

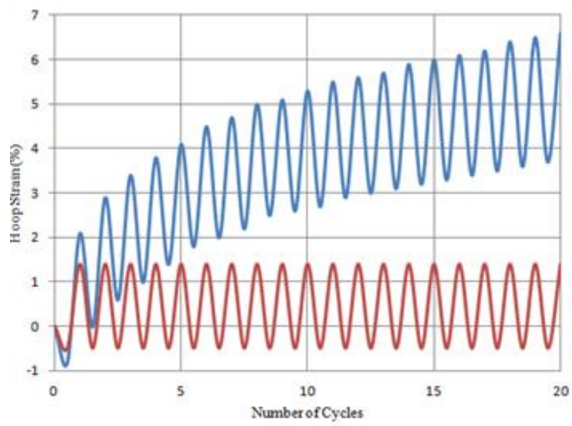


Figure 5b: Hoop Strain at Extrados ID

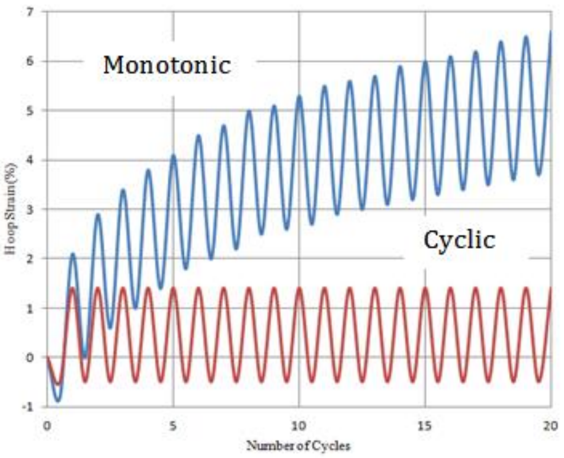


Figure 5c: Hoop Strain at Crown ID
s

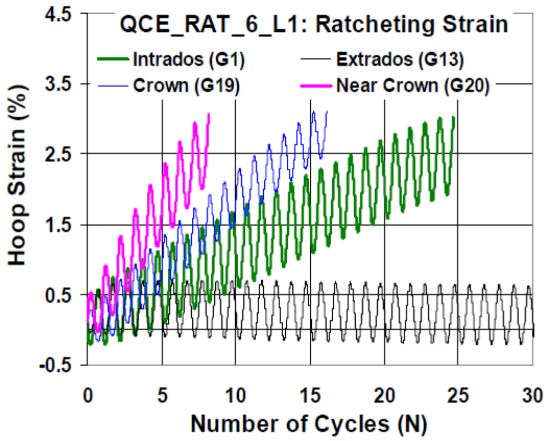


Figure 6: Comparison of accumulated ratcheting strain response with number of cycles at various locations in QCE_RAT_6_L1.[Suzuki *et. al*. 2006]

Moreover, maximum strain accumulation as well maximum strain range was observed near the crown location. It is important to note that the cyclic strain range at crown was varying from 0.8% to 1.2% in different tests (refer to Fig. 6) Corresponding to this strain range the number of cycles to crack initiation as per classical low cycle fatigue assessment or ASME mean fatigue life curve, should have been varying from 5500 cycles to 19000 cycles. These investigations clearly points out the significant influence of the ratchet strain (local accumulation strain) and nonrelaxing mean stress on the low cycle fatigue life of elbows. These ratcheting studies on pressurized elbows 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.

From the present paper, it was observed that, the accumulations of hoop strains are higher at ID than OD at all locations. They are 80%, 35% and 23% for intrados, extrados and crown locations respectively. This is due to that, the inside wall of the elbow is directly in contact with pressurized load, which sustained throughout the analysis. It can be seen clear that strains due to monotonic loading are more effective than that due to cyclic loadings.

From the previous results of accumulative hoop strains on ID and OD, which gave high strains on ID compare to OD, so that we need to focus on ID strains. From the axial strain on ID response (Figs. 7) it is clear that during few initial cycles the response of the material models is same but next few cycles the response of each model differs. First of all, the cyclic model response stabilizes within few cycles, while the other model show continuous decrease in the axial strain value at intrados location and continuous increase in the value at the extrados and crown locations. The percentage of axial strains is higher at crown location 69%, while for the intrados and extrados locations are 45% and 62% respectively. Also it is observed from these figures that cyclic model leads to plastic shakedown within few cycles, while the other show continuous accumulation. In addition it is observed that at the crown location the monotonic in over predicting the response.

From the previous paper [Sumit *et. al.* 2011], Fig. 8, it is also observed that strain range as well as ratchet strain accumulation is more at inner side of crown region. Thus, it supports the experiment's observation that in pressurized elbows crack initiates at the inner side of crown region only.

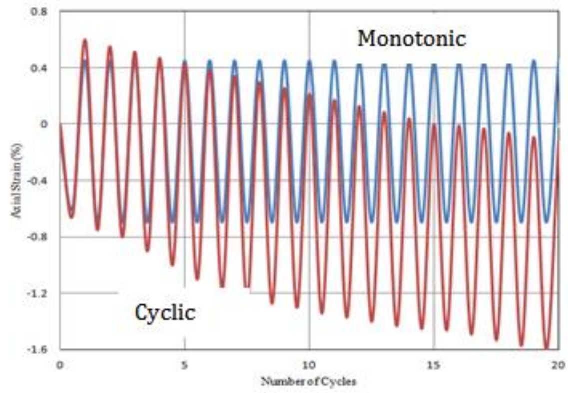


Figure 7a: Axial Strain at Intrados ID

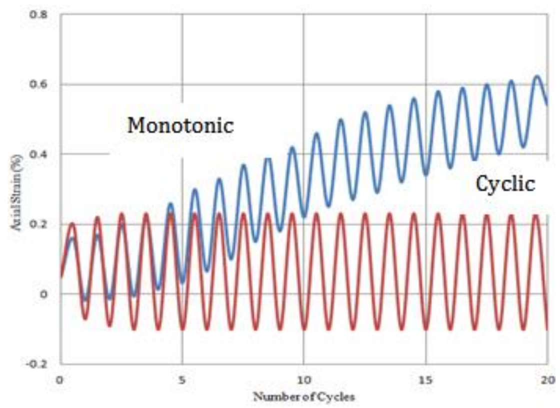


Figure 7b: Axial Strain at Extrados ID

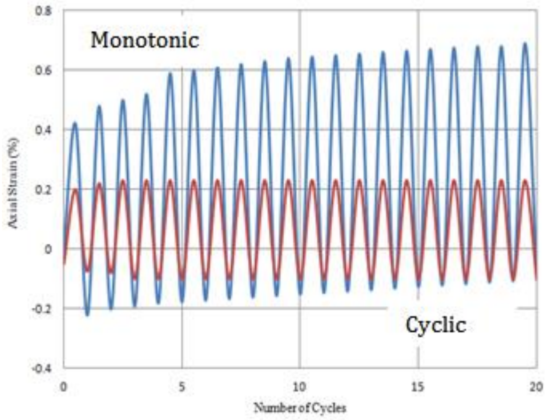


Figure 7c: Axial Strain comparison at Crown ID

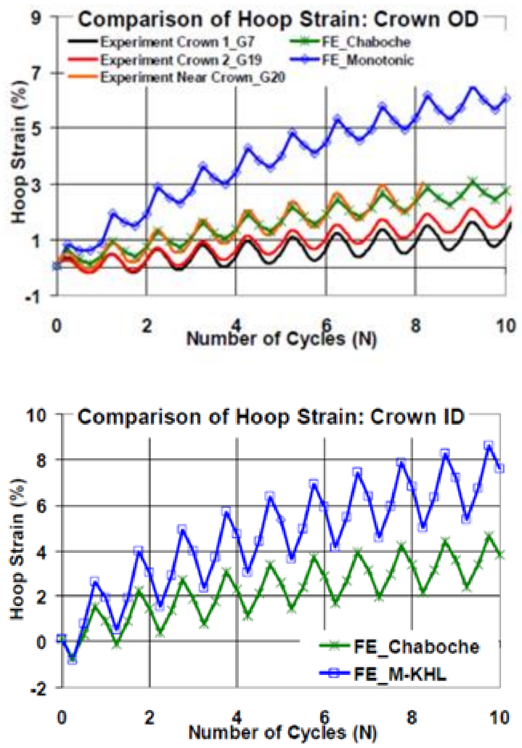


Figure 8: Comparison of FE evaluated ratcheting strain with test recoded at inner and outer surface of Crown [Sumit *et. al.* 2010]

Figs. 9 and 10 show the comparison of accumulated strain and strain range response at crown, in the two cases ID and OD locations respectively, using the two load models. From Figs. 9a and b, it is observed that cyclic model leads to plastic shakedown within few numbers of cycles, while the other show continuous accumulation. On the other hand, monotonic model shows continuously increasing rate of strain accumulation. Accumulated strains at ID were about 15% compare to the case of OD at the end of 20th cycles of loading.

Figs. 10a and b show the comparison of strain range obtained using these two models. In case of monotonic model the hoop strain range was high in first cycle, followed by reduction in next cycle. At the end of 20th cycle, the strain range was higher by 62% in the ID compare to OD for the load cases.

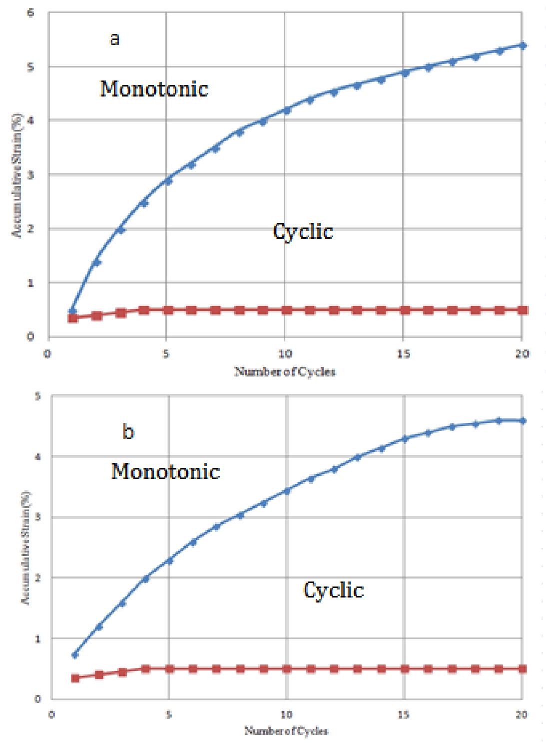


Figure 9: Comparison of Accumulative Strains (a) at ID and (b) at OD

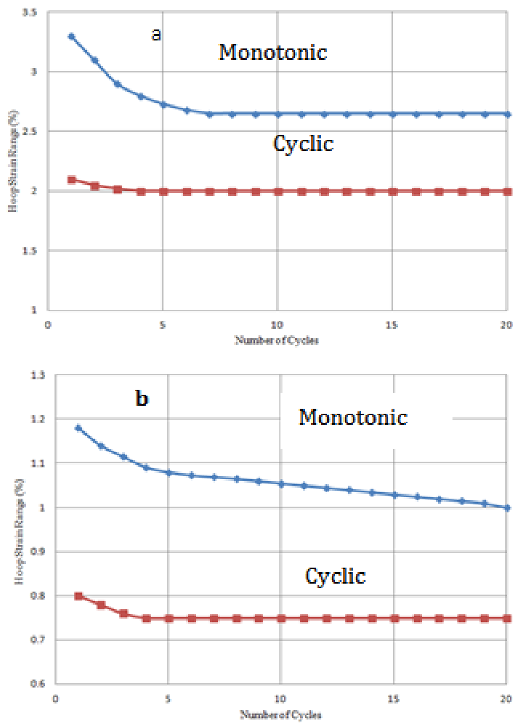


Figure 10: Comparison of Hoop Strain Range (a) at ID and (b) at OD

Conclusions

Among various piping components, elbow exhibit highly strained regions in the piping system because of their flexibility and are vulnerable to failure. In view of this, to understand the fatigue failure mechanisms, fatigue studies were carried out on elbows.

In the previous sub-sections, the results of analysis were discussed and compared among those given by different models. During the analysis the strain at three locations were also recorded.

The comparison of strains was presented for gross responses. It is seen that the critical nodes identified by the FEA of all elbows are near to crown location only. This clears that in most of these cases the failure or the crack initiation will be near to the crown location, which is justified.

From the previous results of accumulative hoop strains on ID and OD, which gave high strains on ID compare to OD and monotonic model shows continuously increasing rate of strain accumulation at ID compare to the case of OD at the end of 20th cycles of loading.

The overall comparison of the model is satisfactory. Still there is a requirement of robust cyclic plasticity model which accounts the extra hardening behavior of material. Generally the elbow is modeled as uniformly thick and leads to considerable ease in modeling. But in actual elbow, its thickness varies along axial as well as circumferential direction. Therefore, further development in cyclic plasticity models and the effect of thickness are essential.

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