FATIGUE-RATCHERING ANALYSIS OF A PRESSURIZED ELBOW

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ABSTRACT

Generally, the engineering components and structures are designed for normal operating loads along with cyclic loads. But when under sustained (primary) loading, components are also subjected to cyclic inelastic (secondary) loading, then with fatigue damage, progressive accumulation of deformation or strain (known as ratcheting) may also take place. Since ratcheting is the progressive inelastic deformation accumulating cycle by cycle, it is not easy to simulate the development of ratcheting accurately. Moreover, it cannot be directly described by the existing cyclic constitutive models established from the experimental results of cyclic straining.

A multi-level test program has been carried out by Reactor Safety Division (Bhabha Atomic Research Centre) to investigate the behavior of typical Nuclear Power Plant (NPP) piping. The test program included monotonic and cyclic testing of piping material at specimens and components level such as elbows. Present work describes the post-test finite element analysis of fatigue-ratcheting test on pressurized elbow.

KEYWORDS

Fatigue , Ratcheting , pressurized elbow

1. INTRODUCTION

Piping systems are used in nearly every industrial facility in the world. Generally they are used to transport materials at a variety of pressures and temperatures. One of the most important components in these systems is the 90^0 elbow. 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 pressure effects. 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 concentrations 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. Historically, elbows have been difficult to analyze accurately. This uncertainty has led to the large safety margins seen in design codes. With the development of the finite element method of analysis (FEA) it has become possible to model the behavior of the elbows using a variety of elements.

Now, in order to understand the fatigue-ratcheting synergy and to evaluate its effect on the fatigue-life of the pressurized components, various tests were conducted by Reactor Safety Division (RSD) of BARC. These tests clearly point out the drastic reduction in fatigue-life of the component. Total four numbers of tests (ERT_SS_1, ERT_SS_2, ERT_SS_3 and ERT_SS_4) were carried out on right angled long radius elbows of 168 mm outer diameter (OD) made of SS304LN stainless steel material. The experiment details are given in [1].

It was observed that, in these pressurized elbow tests cracks initiated at the inner surface of elbows. This implies that, for fatigue-life calculations, stress/strain data was required at the inner 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 Finite Element (FE) analysis of these tests. Thus, detailed 3-D non-linear FE analyses of these ratcheting tests under cyclic displacement controlled loading were performed. The calculated strain range and accumulated strain have been compared with corresponding measured/experimental values.

2. FE ANALYSIS OF FATIGUE-RATCHETING TEST ON ELBOW

2.1 Material Properties

Among various piping components, elbow exhibit highly strained regions in the piping system because of their high flexibility and are vulnerable to failure by fatigue- ratcheting. In view of this, to understand the fatigue-ratcheting failure mechanism, fatigue-ratcheting studies were carried out on elbows. The material used in the present study is SS 304 LN stainless steel, proposed material for Main Heat Transport (MHT) piping system of the Advanced Heavy Water Reactor (AHWR). Mechanical properties of the material are given in table 1.1.

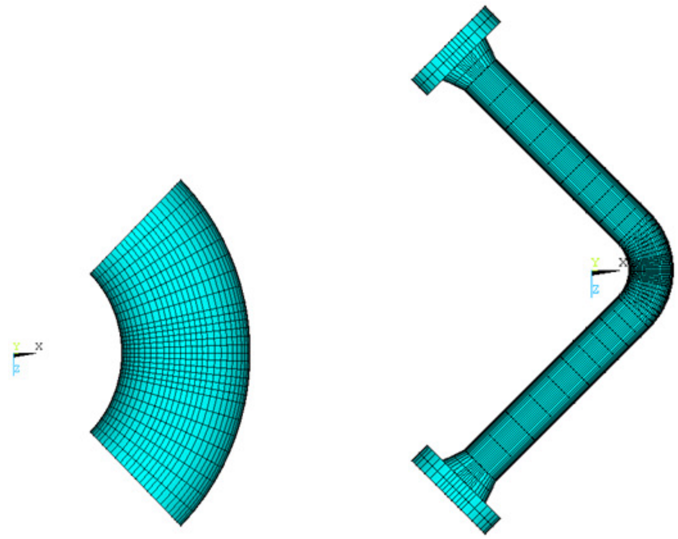
Table 1: Mechanical Properties of the elbow and pipe material [1]

Properties	σ_y (MPa)	σ_u (MPa)	$\sigma_f = 0.5(\sigma_u + \sigma_y)$	Elongation (%)	E (GPa)
Base Metal	345	521	433	65	195

2.2 FE modeling

In comparison to other components of piping system, elbow is more flexible component and it leads to large deformation. Therefore, for the FE analysis of elbows, a fine meshed model is required. In view of the symmetry, only symmetric half domain was modeled, using 20 noded solid elements.

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. The effect of thickness variation on local and global response is studied in [2]. Detailed 3-D non-linear FE analysis was performed on uniform average and actual thickness models in this paper. On the basis of this study it is concluded that for elbow analysis the FE analysis is to be performed using the actual thickness model only. Thus in the present elbow analysis the same actual thickness model is used.



(a) FE model of Elbow (b) FE model of elbow-pipe assembly

Figure 1. Symmetric half domain FE model of elbow and elbow-pipe assembly [2]

2.3 Material Model

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 the ratcheting response of the fatigue-ratcheting test on elbow, various material models were used in FE analysis. Among these, two stress-strain curves (monotonic and cyclic) are used with multilinear kinematic hardening law and one with Chaboche three decomposed rule. These are listed below:

1. Monotonic (or unstabilized) material stress-strain curve with multilinear kinematic hardening law (M-MKHL)
2. Cyclic (or stabilized) material stress-strain curve with multilinear kinematic hardening law (C-MKHL)
3. Chaboche three decomposed rule (Chaboche)

Different parameters such as Load-Load Line Displacement (load-LLD), hoop, axial, and Von-Mises strains were evaluated. The detailed analysis results would be discussed below

2.3.1 FE Analysis of fatigue-ratcheting test ERT_SS_3

Finite element modeling of ERT_SS_3 was done as described in section 2.2. For the cyclic loading, actual loading history of ERT_SS_3 was to be used. Before using this loading history which was recorded by the LVDT's during the tests, some backlash corrections are to be applied. Also there was a requirement of rigid shifting of the L-LLD curve, to obtain the correct match with L-LLD curve so obtained by FE analysis. After all the corrections the actual loading history is as follows: the magnitude of displacement loading cycle is 46mm, in closing, followed by 41mm in opening. The loading was continued for complete 20 cycles. A constant internal pressure of 27.58 MPa is applied.

From the analysis gross response such as load-LLD, hoop strains and axial strains were evaluated and compared with experiment results.

Figure 2, 3 and 4 show the comparison of load-LLD response of ERT_SS_3. In figure 2 for the 1st cycle of loading, load-LLD response of FE analysis with Chaboche model shows closer matching with experiment. The predicted load amplitude and width of the loop are also close to experimental values. In comparison to this, FE analysis with M-MKHL and C-MKHL models are not able to accurately simulate 1st cycle of Load- LLD response loop.

On comparison of 5th cycle in figure 3, it was observed that there was a close match of load-LLD response during the unloading by M-MKHL model and Chaboche model, whereas the analysis response obtained by C-MKHL differs to large extent. The width of the loop was not exactly matching in any of the material model.

Similar trend was observed for 20th cycle, as shown in figure 4.

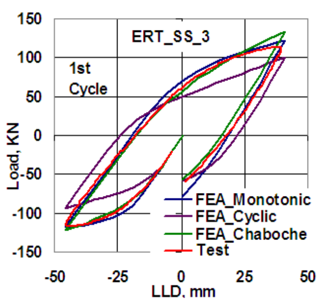


Figure 2. Comparison of load-LLD response for 1st cycle loading of ERT_SS_3

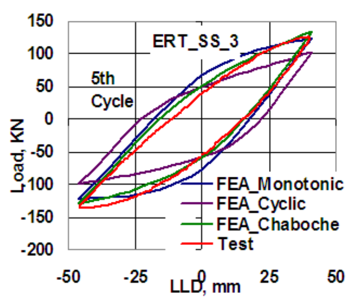


Figure 3. Comparison of load-LLD response for 5th cycle loading of ERT_SS_3

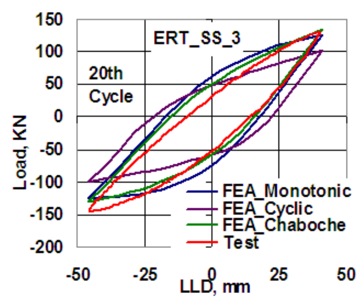


Figure 4. Comparison of load-LLD response for 20th cycle loading of ERT_SS_3

Apart from gross deformation response, local strain field were also compared. These comparisons were made at the intrados, crown and extrados location from the analysis results obtained using different material models.

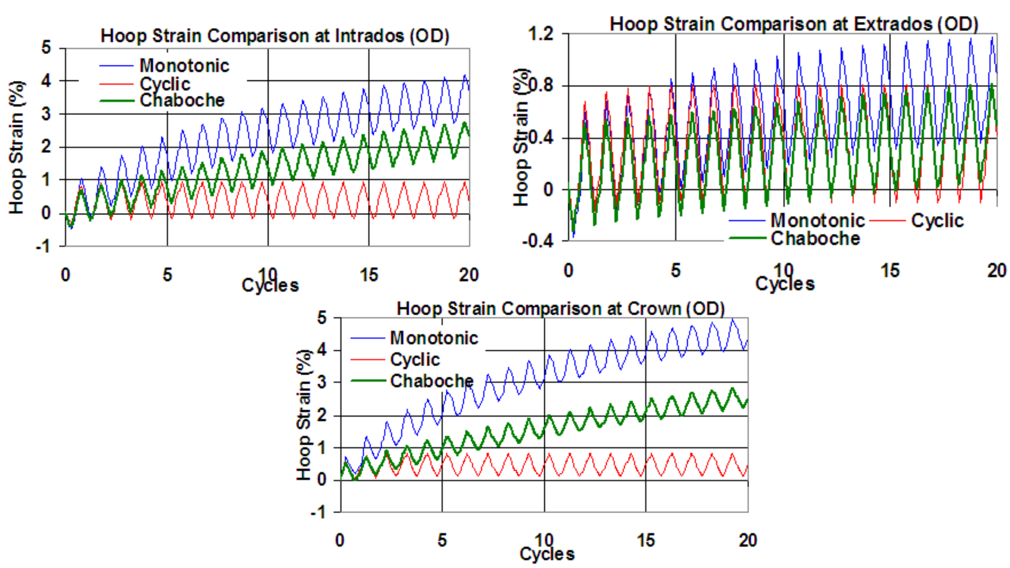


Figure 5. Comparison of Hoop Strain response of ERT_SS_3 at OD

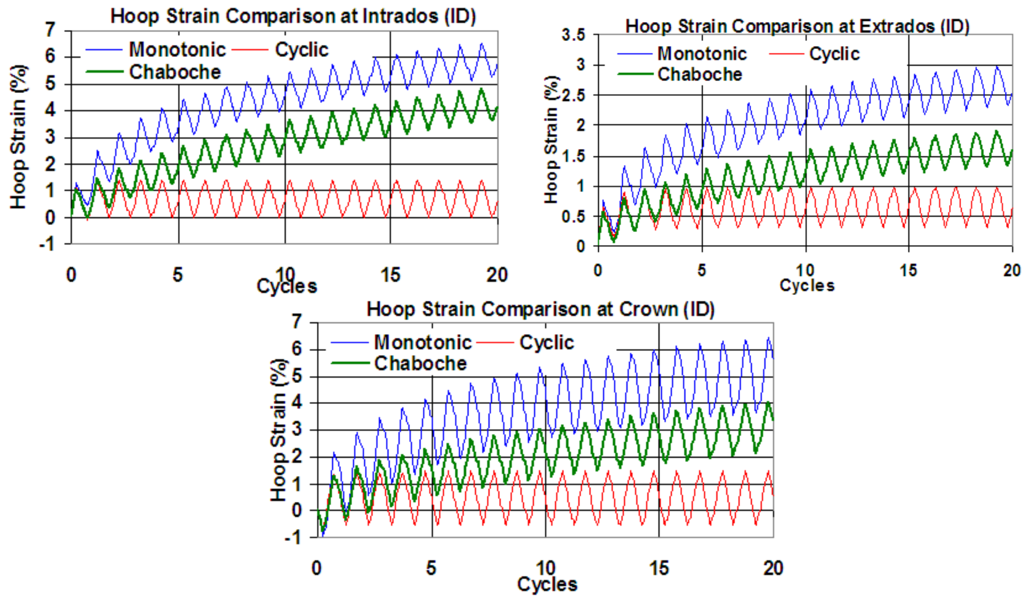


Figure 6. Comparison of Hoop Strain response of ERT_SS_3 at ID

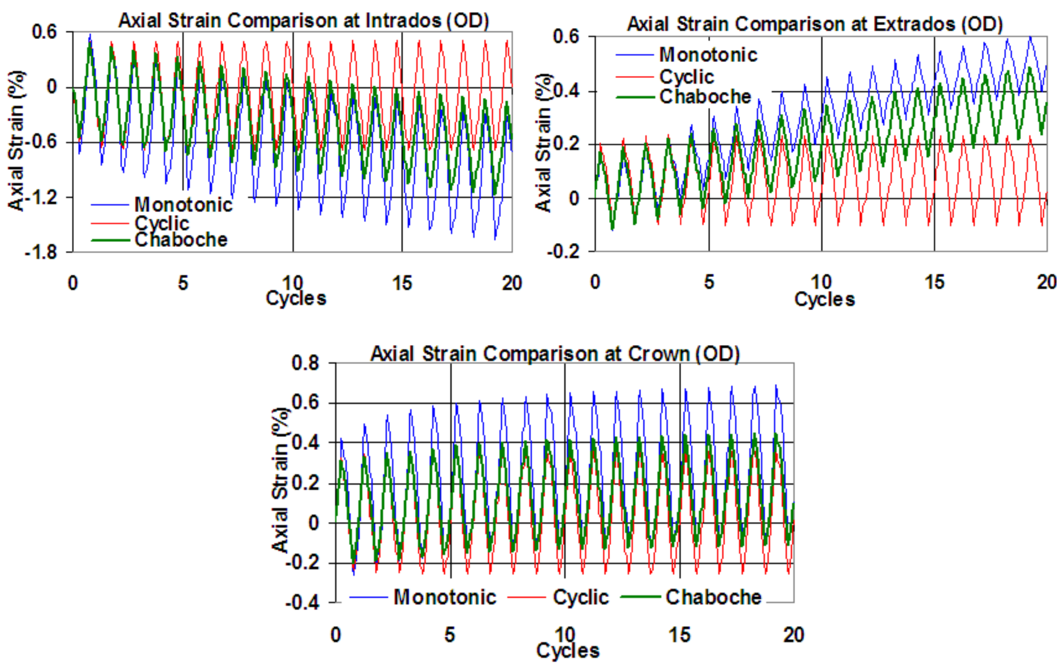


Figure 7. Comparison of Axial Strain response of ERT_SS_3 at OD

Figure 5 and figure 6 shows the comparison of hoop strain, using the three material models at OD and ID respectively. From the figures 5 and 6, it is seen that the accumulation of hoop strain (ratcheting strain) will be more at crown in comparison to intrados and extrados. This clears that in most of the cases the failure or the crack initiation will be near to the crown location.

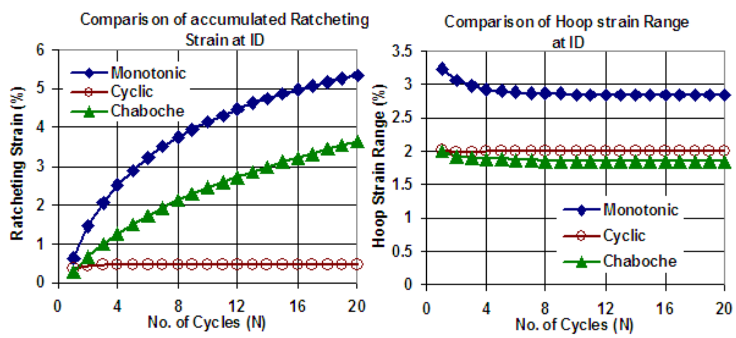
From the axial strain response (Figure 7) it is clear that during few initial cycles the response of all 3 material models is same but after few cycles the response of each material model differs.

First of all the C-MKHL model response stabilizes within few cycles. While the other two models show continuous decrease in the axial strain value at intrados location and continuous increase in the value at the extrados location and crown location.

Also it is observed from these figures that C-MKHL model leads to plastic shakedown within few cycles, while the other two show continuous accumulation. In addition it is observed that at the crown location the M-MKHL as well as Chaboche model is over predicting the response. Similar response was observed at extrados. It is observed that the accumulation of hoop strain is more at ID compared to OD at all intrados, extrados and crown location. This is because the inside wall of the elbow is directly in contact with the pressurized water which is sustained throughout the analysis.

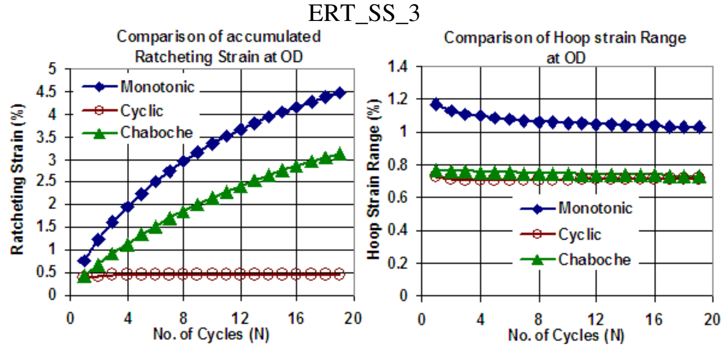
Figure 8 and Figure 9 shows the comparison of accumulated ratcheting strain and strain range response at crown location at ID and OD respectively, using the three material models.

From the figures 8 (a) and 9 (a); it is observed that C-MKHL model leads to plastic shakedown within few numbers of cycles, while the other two show continuous accumulation. After few initial cycles Chaboche model shows linear rate of strain accumulation. On the other hand, M-MKHL model shows continuously decreasing rate of strain accumulation. Accumulated ratcheting strain is about 0.45 %, in case of C-MKHL model, 3.64% in case of Chaboche model and 5.34% in case of M-MKHL model, in case of ID, while it is about 0.454 %, in case of C-MKHL model, 3.13% in case of Chaboche model and 4.46% in case of M-MKHL model, in case of OD, at the end of 20 cycles of loading.



(a) Comparison of accumulated ratcheting strain (b) Comparison of hoop strain range

Figure 8. Comparisons of accumulated ratcheting strain and hoop strain range at crown at ID of ERT_SS_3



(a) Comparison of accumulated ratcheting strain (b) Comparison of hoop strain range

Figure 9. Comparisons of accumulated ratcheting strain and hoop strain range at crown at OD of ERT_SS_3

Figure 8 (b) and 9 (b) shows the comparison of strain range obtained using these three models. At the end of 20^{th} cycle, the strain range was highest in case of M-MKHL model (2.84%), in comparison to Chaboche model (1.84%) and C-MKHL model (2.0%) at ID. Similarly the strain range was highest in case of M-MKHL model (1.03%), in comparison to Chaboche model (0.732%) and C-MKHL model (0.712%) at OD. In case of M-MKHL model the strain range was high in first cycle, followed by reduction in next cycle.

After studying the response of ERT_SS_3 it is seen that this same quality of response almost resembles with the quality of response of ERT_SS_1 elbow analysis which was carried out by Sumit et al [1]. Thus it can be concluded the analysis response is same for any type of loading conditions.

2.4 Summary of local strain comparison

In the previous sub-sections the results of analysis were discussed and compared among those given by different material models. The comparison with experiments was presented for gross responses like load-LLD. During the tests the strain at outer surface of crown location was also measured. It is seen that the critical nodes identified by the FE analysis of all 3 elbows are near to the crown location only. This clears that in most of the cases the failure or the crack initiation will be near to the crown location, which is justified.

The overall comparison with the Chaboche material model is satisfactory. Still there is a requirement of robust cyclic plasticity model which accounts the extra hardening behavior of material. Therefore further development in cyclic plasticity models is essential.

2.5 Acknowledgements

I thank Mr. K. K. Vaze (Associate Director RD & DG and Head RSD, BARC) and Mr.Vivek Bhasin (Head RSS, RSD, BARC) for giving me this glorious opportunity to work with the best in the field of Cyclic Plasticity and Ratcheting and all help that they extended to me during the course of this project.

I am greatly indebted to **Mr. Suneel Gupta** (SO/F, RSD, BARC) and **Mr. Sumit Goyal** (SO/D, RSD, BARC) for the encouragement and co-operation they have extended to me. Their valuable knowledge has helped me successfully complete my work at BARC, Mumbai. They have guided me during the entire course of project. This includes introduction to basic subject of fatigue-ratcheting, finite element simulation techniques, interpretation of data. They gave me numerous suggestions to bring the work to advance level.

3. CONCLUSIONS

From the L-LLD graphs of Elbow analysis it is clear that Chaboche material model almost matches with the experiment compared to the M-MKHL material model and C-MKHL material model. In case of the accumulation of ratcheting strain the value of C-MKHL model stabilizes within few cycles due to plastic shake down; while the value corresponding to the M-MKHL model is predominately over predicting. However the Chaboche material model shows continuous accumulation of ratcheting strain like M-MKHL model but its value is less than M-MKHL model. From this it can be concluded that Chaboche material model can be used for the simulation of the strain response also.

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