

APPLICATION OF FINITE ELEMENT METHOD FOR LOW CYCLE FATIGUE ANALYSIS FOR STEEL

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Abstract

The experimental estimation of the fatigue curve is quite expensive and complex. It is very difficult to create an actual reactor's working environment, such as extreme temperatures, etc. Hence, the finite element method can be employed for the investigation, estimation of the fatigue behaviour of the steel, and plotting the fatigue curve, using this curve, the fatigue mechanism can be studied in detail.

In this research, we have created a finite element model for investigating the low cycle fatigue behaviour of steel using LS-Dyna and ANSYS. A strain-controlled low-cycle fatigue test experiment at 300 °C on AISI 304L steel for 0.3% strain was carried out and the results of it are used to estimate the material model parameters and validate the simulation results. The simulation model is created to replicate the experiment. The simulation results are compared with the experimental results. It is observed that the simulation results are close to the experimental results. On the bases of the presented results, it can be concluded that the presented methodology can be employed for the low cycle fatigue analysis for the approximate prediction of the fatigue life and the change in the material behaviour with the increase in the number of loading cycles.

Keywords: LCF, strain-controlled fatigue testing, AISI304L steel, FEM, Numerical Investigation

1. INTRODUCTION

Low cycle fatigue is the term used for the fatigue failure if the elasto-plastic failure of the component above the yield stress is reach at low cycle number of loading cycles (i.e., $<10^5$) [1].

The low cycle fatigue phenomena can be divided into two stages in microstructure evolution with four steps [2]. The beginning of the fatigue damage i.e., indicator of the initiation of surface cracking can be observed during the step 1 with the unstable softening of the material [2]. During step 2, we can observe gradual crack propagation inwards of the component, this stage is also termed as stage I crack growth. In step 3, which is also known as stage II crack growth, we can observe the high tensile stress planes propagating perpendicular to the applied load [2]. Once the crack is fully grown, fracture occurs this is the step 4.

In the presented research, experiment for the strain controlled low cycle fatigue test for 0.3% strain at 300 °C on AISI 304L steel is performed and a finite element model for the numerical simulation of the same experiment is prepared. For the preparation of FE model, LS-DYNA and ANSYS software's are used. Combined isotropic and kinematic hardening are applied to define the material model for the numerical simulation. The isotropic hardening curve and kinematic hardening parameters are estimated with the help of the experimental results. The simulation results are compared with the experimental result for the validation of the numerical model. The numerical model gives the results close to the experimental results similar like in [3,4].

2. MATERIALS AND INVESTIGATION METHODS

2.1. Experimental Investigation of LCF Experiment

2.1.1. Material and Specimens

Creusot Loire Industries manufactured the test specimen from AISI304L stainless steel which is annealed at temperature 1050 °C to 1100 °C up to 2hrs. This steel is widely selected for the structure operating in the high temperature, pressure fluctuating loading, etc. and these conditions are responsible for the thermomechanical fatigue [3].

Table 1 presents the mechanical properties of steel and **Figure 1** shows the drawing of the experimental specimen.

2.1.2. Low Cycle Fatigue Test Method

The low cycle fatigue test is carried out using Instron Model 8801. LCF testing is carried out at 300°C and for the strain amplitude of 0.3% strain-controlled environment, according to the ASTM E606 Standard Practice for Strain-Controlled Fatigue Testing.

Table 1 Mechanical properties of AISI 304L steel

Temperature, °C	Yield Stress, MPa	Ultimate Tensile Strength, MPa	Elongation, %	Youngs Modulus, GPa
20	278	610	84	200
300	220	499	42	157

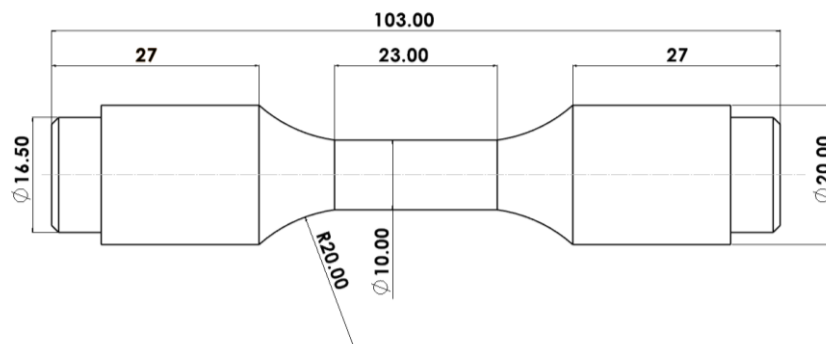


Figure 1 LCF test specimen drawing

2.2. Numerical Simulation for LCF

2.2.1. Finite Element Model

The three-dimensional model for the finite element modelling is prepared by referring the experimental specimen drawing (**Figure 1**). As it can be observed in **Figure 1**, the test specimen is symmetric. To reduce the computational time finite element model is prepared for the 1/4th portion of the centre part of specimen is prepared.

For the modelling of the specimen, 437 constant stress solid elements are used to model the specimen in LS-DYNA. The above **Figure 2** represents the meshed finite element model. For the model prepared in Ansys 8-node cube shaped SOLID185 element is employed for the specimen modelling. The selected elements for both the software's are the 8-node cube shaped element with three translation DOF at each node in x, y, and z directions.

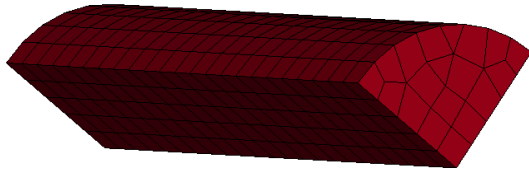


Figure 2 Finite Element Meshed Model

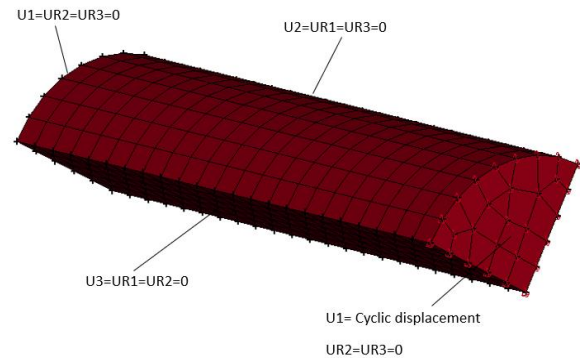


Figure 3 Applied boundary conditions for finite element model

The applied boundary conditions to the finite element model can be observed in **Figure 3**. The cyclic displacement (i.e., loading) is applied in the U1 direction to the front flat face of the specimen according to the loading pattern.

2.2.2. Material Model

In the current research, for the modelling of the proper material behaviour combined isotropic and kinematic hardening is employed. In LSDYNA MAT_153 damage_3 material model is selected for the material modelling for the numerical simulation. This model consists of the kinematic hardening combined with the isotropic hardening and a damage model to model the LCF and failure. In case of ANSYS, user defined material is modelled using the experimental data.

2.2.2.1. Isotropic Hardening

The isotropic hardening curve used to define in LS-DYNA and ANSYS is estimated using experimental results. Isotropic hardening curve for 0.3% strain is presented in the below **Figure 4**.

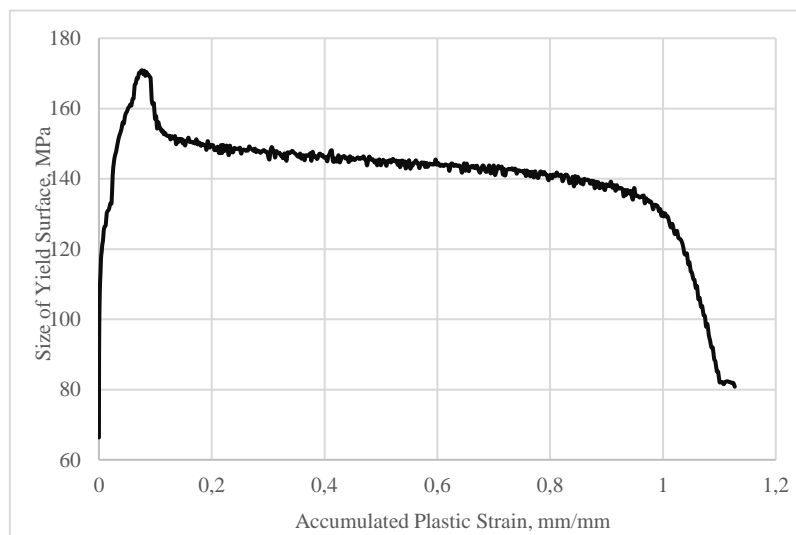


Figure 4 Evolution of the size of the yield surface as a function of the accumulated effective plastic strain of AISI304L steel for 0.3% strain

In the above **Figure 4**, the isotropic hardening curve used for the numerical modelling of the LCF test is presented. The above curve (**Figure 4**) is used for the LS-Dyna simulation and in case of the ANSYS only a

part of it until the curve is ascending. This is because, the ANSYS does not accept the values less than the previous entered value.

2.2.2.2. Kinematic Hardening

Chaboche kinematic hardening model [5] (equation 1) is used to estimate the kinematic hardening parameters for ANSYS Workbench. And for the parameters used in LS-Dyna (equation 2), which is Armstrong and Frederick material model [6] is used.

$$d\alpha_i = \frac{2}{3} C_i d\epsilon^p - \gamma_i \alpha_i d\epsilon^p \quad (1)$$

$$\alpha_j = 2/3 C_j \bar{\epsilon}^{pl} - \gamma_j \alpha_j \bar{\epsilon}^{pl} \quad (2)$$

Where C, γ are the hardening parameters.

$\dot{\epsilon}^{pl}$ and $\bar{\epsilon}^{pl}$ is the plastic strain and accumulated plastic strain respectively.

Material parameters used for the numerical modelling of the material are represented in **Table 3**, below.

In the computational model created with ANSYS, the kinematic component (C1, γ 1, C2, γ 2, C3, γ 3,) are calibrated using second half of the 1000th cycle and for the LS-DYNA 10000th cycle is used, the estimated values of the parameters are represented in **Table 4**.

Table 3 Material Properties used to describe the AISI 304L Steel at 300 °C for 0.3% strain

Material Property	Value
<i>Youngs Modulus, E, GPa</i>	157
<i>Poisson's ratio ν</i>	0.27
Yield Stress, σ_y , MPa	220

Table 4 Kinematic harenig parameters estimated for the strain range of 0.3%

	C ₁ (MPa)	γ_1	C ₂ (MPa)	γ_2	C ₃ (MPa)	γ_3
LS-DYNA	42.160	0.07284	322	0.430	4000	5.6
ANSYS	15482.86	2427.214	16950.62	2135.42	61446.98	268.889

2.2.3. Specimen Loading

A fully reversed triangular waveform displacement is applied to the specimen along the axial direction for the numerical simulation, **Figure 5**.

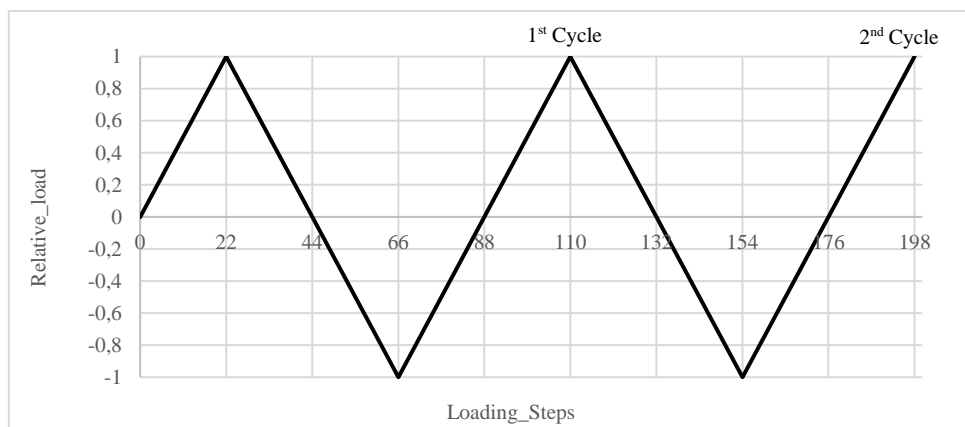


Figure 5 Waveform of cycle load used for numerical simulation

Displacement for the 0.3% strain model is applied such that, the 1st cycle of the tension loading cycle starts at the absolute zero, which is 1/4th of the full cycle. The tension 1st half loading cycle starts at -1 and continues till 1 and the compression 2nd half loading cycle starts at 1 and continues till -1.

3. RESULTS

3.1. LCF Test Results

The new experimental data for creating the guidelines for the improvements for the assessments of environmental fatigue damage was obtained under the project INCEPA-PLUS. These experimental results are used to prepare the simulation model and validate the obtained simulation results.

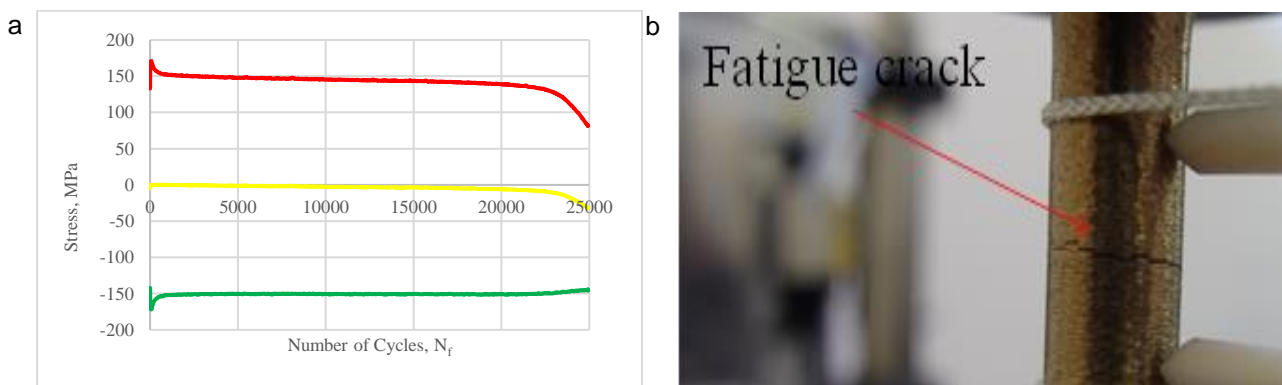


Figure 6 a) Maximum stress v/s number of cycles experimental results at strain amplitudes of 0.3% and b) specimen after failure

The experiments performed at strain amplitude of 0.3% was chosen for the validation of the proposed methodology. **Figure 6.**, shows the experimental result curve and the failed specimen. The specimens showed cyclic softening during the tests. In the experimental test, the failure of the specimen is assumed when the stress level drops 25% below the level of stabilized cycles.

3.2. Simulation of Fatigue Test

Numerical simulation of the fatigue experiment of AISI 304L steel was carried out applying the finite element method. For this purpose, LS-DYNA and ANSYS Workbench were chosen. The validation of the numerical methodology is done by comparing the obtained stress versus cycles values with the values determined experimentally [4].

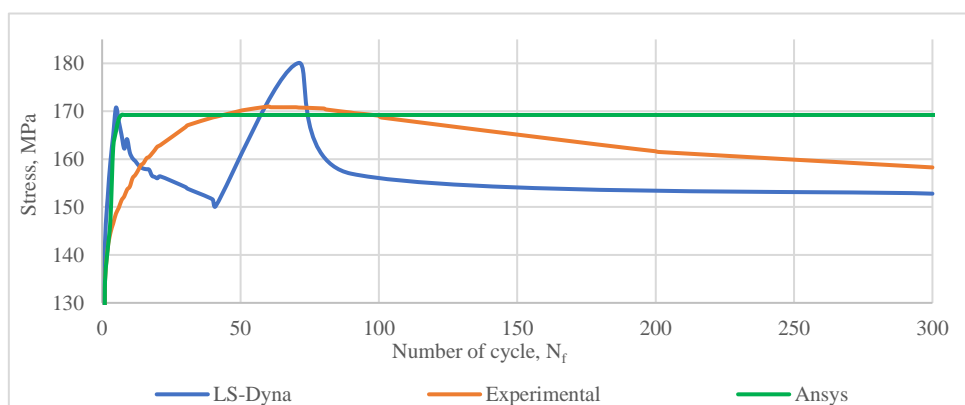


Figure 7 Maximum stress versus number of cycles curve for experimental and simulation results

The numerical simulation of the LCF test is carried out at 0.3 strain amplitude. The experimental and simulation results are represented by plotting the curve maximum stress versus number of cycles (**Figure 7**) and stress versus strain for the loading cycle (**Figure 8**).

The experimental results exhibit the cyclic softening behaviour, because the stress amplitude decreases as the number of cycles increases starting from the 92nd loading cycle (**Figure 7**).

In case of ANSYS Workbench results, it can be observed that the ANSYS is not able to catch the softening behaviour of the material due to the fact since the ANSYS do not accepts the negative slope for the isotropic hardening, i.e., we cannot enter the values smaller than the previous entry. Therefore, it was not possible to define the material softening behaviour from the experimental results in ANSYS.

The results from the LS-Dyna, for the initial few cycles the curve shows fluctuation from the experimental results but as the number for cycles proceeds further the curve tends to go near the experimental result curve. LS-Dyna results show the cyclic softening behaviour of the material.

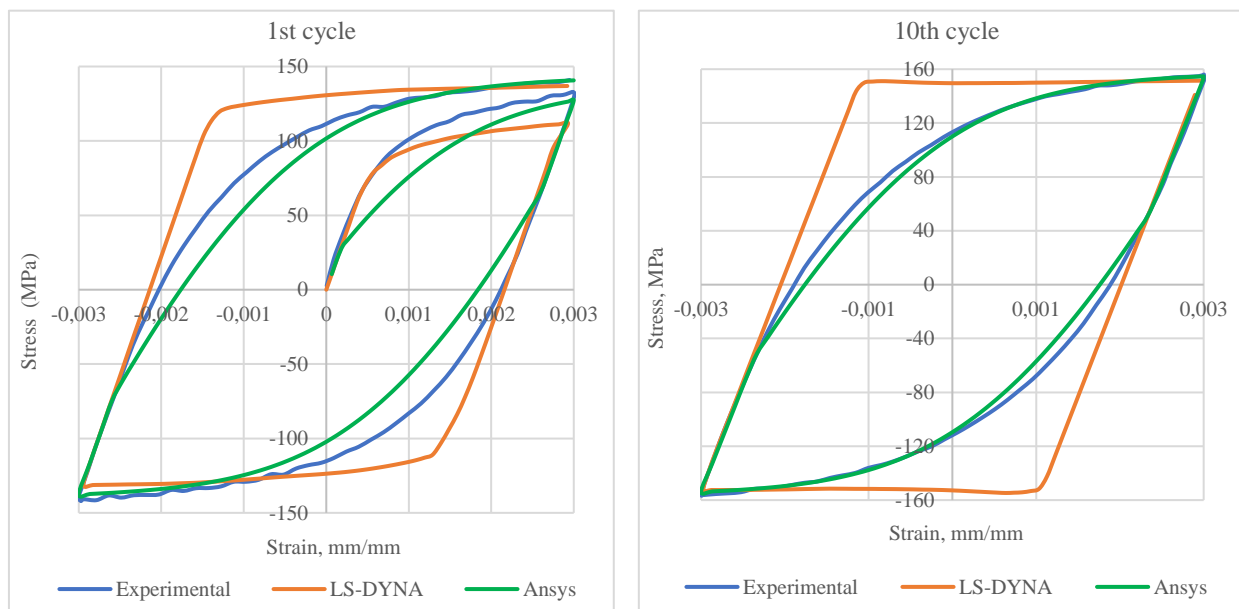


Figure 8 Stress Versus Strain curve plotted for experimental and numerical simulation results

The stress versus strain curve (hysteresis loop) of the experimental results and the simulation results for both the models is represented for 1st and the 10th cycle in the **Figure 8**. The plotted curve of hysteresis loops displays good agreement between the ANSYS and the experimental results. The LS-Dyna results are close to the experimental results but at present stage of research wasn't received the proper shape of the loop. In the future with the improvements in the material model and refining the finite element model the curve of the hysteresis loops will display better agreement between numerical simulation and the experimental results.

4. CONCLUSIONS

The presented research consists of the strain controlled low cycle fatigue testing and numerical simulation of the same using finite element method on AISI304L steel for 0.3% strain at 300 °C. Finite element model for the simulation was prepared with the same conditions as of during the experiment. For the proper modelling of material behaviour, combined isotropic and kinematic hardening is employed. And the material parameters are estimated using the experimental data and are presented in this article. For the kinematic hardening different rules are employed for both software's. Chaboche kinematic hardening rules is used for the ANSYS model and for the LS-Dyna model Armstrong and Frederick kinematic hardening rule is used.

The experimental results of the AISI304L steel displayed the cyclic softening behaviour for the cyclic loading. The numerical simulation from the ANSYS for initial few cycles the results showed agreement with the experimental results but as the cycle increased the result showed the deflection up to 13.43% and then after at the end of the simulation the difference between the ANSYS and experimental results is 6.69%. ANSYS was not able to capture the cyclic softening behaviour of the material which was observed in the experimental results. The numerical results estimated with LS-Dyna, for initial few cycles it showed the deflection from the experimental results up to 12% as the loading cycle proceeds the simulation results gets better and tends close to the experimental results with 3.9% for difference but this software displayed the softening behaviour for the material.

The ANSYS software can only be used for the hardening behaviour material because it does not accept the negative slope for the isotropic hardening curve and for the modelling of the softening behaviour of the material this negative slope of the curve is important. The LS-Dyna showed the softening behaviour in the results and gives close results with the experimental results with the deflection. With the improvements in the material model and refining the finite element model this software can be employed for the LCF numerical analysis to estimate the change in the behaviour of the material with the increase in the loading cycles and to predict the approximate fatigue life of the material undergoing cyclic loading.

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