Simulation of Low Cycle Fatigue with Abaqus/FEA

K.K.G.K.D.Kariyawasam\textsuperscript{1} and H.M.Y.C. Mallikarachchi\textsuperscript{1}

\textsuperscript{1}Department of Civil Engineering
Faculty of Engineering
University of Moratuwa
Moratuwa
SRI LANKA

E-mail: civilkasun@gmail.com

Abstract: Low cycle fatigue is an important design consideration for large steel structures and metallic machine components. Accurate prediction of fatigue endurance is essential to design the elements subjected to fatigue. The design guidelines given in codes of practices are applicable only to simple shapes and laboratory experimental verification is costly. Therefore simulation using finite element software is becoming popular. This paper demonstrate successful coupling of Abaqus/FEA and fe-safe software in predicting the uni-axial fatigue behaviour of a stainless steel specimen. The simulated results are verified against experimental results available in literature. Sensitivity to surface roughness and material model were examined.

Keywords: Low cycle fatigue, fatigue simulation, elastic plastic fatigue analysis

1. INTRODUCTION

A material can fail well below its monotonic strengths when it is subjected to repeated loading. This phenomenon is known as fatigue. Fatigue can happen progressively, even when the applied loads are individually too small to cause failure. Most of the structural elements are subjected to various types of vibrations over their lifespan. A structure may fail with lower number of cycles when it is subjected to higher amplitudes of vibration (low-cycle fatigue) or the same structure may fail with higher number of cycles but under lesser amplitude of vibration (high-cycle fatigue). While the mechanical engineers are always concerned about fatigue when designing machine components, the civil engineers concern fatigue damage mainly in steel bridges and tall steel structures that are subjected to wind and earthquake induced vibrations.

Fatigue damage estimation methods given in most codes of practices are for simple structural shapes. On the other hand testing large structural components for vibrations is costly. Australian code AS4100 defines a concept called the detailed category ($f_{\text{rn}}$) for different components. Detail category takes in to account many fatigue inducing properties to estimate the appropriate endurance curve. However there are still a number of unidentified potential problems in fatigue design specifications given in codes of practices (Dean B. & Mendis P.A., 2000). Therefore fatigue modelling through computer software is becoming popular. These finite element software uses damage estimating algorithms to estimate the damage initiation and propagation. All fatigue inducing properties such as surface finish, temperature, stress concentrations can be included for accurate estimations.

Low cycle fatigue simulation has performed in the literature mostly for a selected strain amplitude level. (Glodež & Knez, 2007) (G.Staudinger & T.Reiter, 1997) This paper relates the endurance to several strain levels by performing multiple simulations.
2. FATIGUE ANALYSIS

Fatigue endurance under uniaxial fatigue for different constant amplitude strain levels are presented in the form of S-N curves. S-N curves are widely used to estimate fatigue damage by generalising for different shapes, different loading histories and different materials.

Generalisation of constant strain amplitude test data for complex loading histories is done using Miners rule together with Rain-flow cycle counting method. Generalisation for shape, mean stress and other factors are done through the correction factors. Figure 1 presents stress-strain relationship under fatigue loading approximated using uniaxial fatigue formula.

2.1. Uniaxial Fatigue

Local strain life fatigue analysis presumes that the stain life behaviour of the local stress concentration is similar to a larger uniform section tested with equalling stresses and strains. Local strain life methods are suitable for finite element models because the stress strain relationship at all locations are known. Cyclic stress (σ) strain (ε) relationship which represents the tips of the stabilized hysteresis loop coordinates is represented by,

$$\epsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{n'}$$

where

- $\epsilon$ - cyclic elastic modulus
- $K'$ - strain hardening coefficient
- $n'$ - strain hardening exponent

The total (elastic & plastic) strain-life relationship for uniaxial fatigue (Coffin-Mansion formula) is defined as,

$$\frac{\Delta \epsilon}{2} = \frac{\sigma_f'}{E} (2N_f)^b + \epsilon_f' (2N_f)^c$$

where

- $\Delta \epsilon$ - applied strain range
- $2N_f$ - number of reversals to failure
- $b$ - fatigue strength exponent
- $\sigma_f'$ - fatigue strength coefficient
- $c$ - fatigue ductility exponent
- $\epsilon_f'$ - fatigue ductility coefficient

![Figure 1. Strain-life Relationship (Coffin-Mansion)](image)

Local strain-life analysis is a fatigue crack initiation criterion. There are several correlations such as Morrow’s mean stress correlation to take account of the mean stress effect. (Fe-safe, 2002)
2.2. Multi-Axial Fatigue

In practice many structures experience multi-axial fatigue. Use of uniaxial methods for multi-axial fatigue may give overestimates of the life. The fatigue cracks are usually initiated from the surface. Combination of in-plane stresses and out-of-plane stresses on the surface creates tri-axial stress distribution. Multi-axial fatigue theories concentrate on this condition. Different criterions have been proposed by researchers.

Brown miller equation is a widely used multi-axial fatigue criterion. Brown miller equation with morrow's mean stress correlation can be expressed as,

$$\frac{\Delta \gamma_{\text{max}}}{2} + \frac{\Delta \varepsilon_n}{2} = 1.65 \left( \frac{\sigma_f - \sigma_{\text{mm}}}{E} \right) (2N_f)^b + 1.75 \sigma_f (2N_f)^c$$

(3)

where,

$\Delta \gamma_{\text{max}}$ Maximum shear strain

$\Delta \varepsilon_n$ Normal strain range

$\sigma_{n,m}$ Mean normal stress on the plane

3. SIMULATING FATIGUE

Zhou, et al., 2008 have conducted an experimental study on the low cycle fatigue of stainless steel reinforcement bar specimens. An attempt is made to simulate the standard uniaxial fatigue test done by Zhou, et al using ABAQUS/FEA and fe-safe commercial finite element software. Experiment is modelled in Abaqus to obtain the maximum stresses and strains under a specified loading condition first. Then the stress-strain data is imported to fe-safe to predict the fatigue behaviour under cyclic loading.

3.1. Material Properties

The simulation was done for stainless steel 316LN test specimens. The cyclic properties and fatigue properties extracted from the literature are given in Table 1

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Cyclic Elastic properties (Zhou, et al., 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young’s modulus (MPa)</td>
</tr>
<tr>
<td></td>
<td>199817</td>
</tr>
<tr>
<td>Cyclic Plastic properties (J.Shita, et al., 2013)</td>
<td></td>
</tr>
<tr>
<td>Yield stress(MPa)</td>
<td>Plastic strain</td>
</tr>
<tr>
<td>270</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>0.0025</td>
</tr>
<tr>
<td>330</td>
<td>0.0075</td>
</tr>
<tr>
<td>350</td>
<td>0.0125</td>
</tr>
<tr>
<td>370</td>
<td>0.0175</td>
</tr>
<tr>
<td>400</td>
<td>0.04</td>
</tr>
<tr>
<td>Fatigue Properties (Fe-safe, 2014)</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>-0.0835</td>
</tr>
<tr>
<td>c</td>
<td>-0.5142</td>
</tr>
<tr>
<td>$\varepsilon_i$</td>
<td>0.476</td>
</tr>
<tr>
<td>$\sigma_f'$</td>
<td>703.4</td>
</tr>
</tbody>
</table>
3.2. Material model

The hardening model is very important in simulating the fatigue behaviour. A linear kinematic hardening model or a nonlinear isotropic/kinematic hardening model can be used in Abaqus to simulate the behaviour of materials that are subjected to cyclic loading. The evolution law in these models consists of a kinematic hardening component (which describes the translation of the yield surface in stress space) and, for the nonlinear isotropic/kinematic hardening model, of an isotropic component (which describes the change of the elastic range). (Abaqus, 2013)

The initial transient behaviour is not important since the material comes to stabilized cyclic response easily. However, the stabilized cyclic response is present in majority of the fatigue life. Therefore, nonlinear kinematic hardening model is used which is similar to that’s described in (G. Staudinger & T. Reiter, 1997)

3.3. Modelling with ABAQUS

Abaqus standard is used for this analysis. 3D20R solid elements with varying mesh size are used in order to model the stainless steel specimen. A finer mesh was used to model the central region to obtain a detail stress distribution.

General static analysis is performed neglecting the geometric nonlinearity. Bottom grip was restrained to move in all degrees of freedom and top grip was allowed to translate along the longitudinal axis of the specimen as shown in figure below.

![Figure 2. Idealized boundary condition in Abaqus](image)

The model was run for different strain levels to construct the stress strain behaviour. Figure shows strain distribution for a simulation subjected to 1.77% overall strain. Figure illustrates the cyclic stress strain behaviour of a node at the centre of the specimen for the same 1.77% strain amplitude. The strain gauge in the experimental investigation performed by Zhou, et al., 2008 is located between the end points of the middle uniform cylindrical area. Therefore the strain values presented here refers to the same region.
3.4. **FE-SAFE fatigue analysis**

Both the stress and strain datasets for each strain level are imported from Abaqus to the FE-SAFE software. By default FE-safe assumes the stress datasets as elastic blocks. There are two methods that can be used for elastic-plastic fatigue estimation.

1. Using an elastic block with Neuber’s rule
2. Using an elastic plastic block (elasto-plastic FEA is required)

The calculation of plastic strain where necessary is performed using elastic to elastic-plastic correlation (biaxial Neuber’s rule) in the first method. But these correlations are applied to nodes individually. Therefore no stress redistribution is allowed. Hence this method is not suitable especially when large amount of material are subjected to plastic stresses. (Fe-safe, 2014)
Elastic plastic analysis feature in fe-safe requires elastic plastic stress strain datasets for finite elements which is more accurate. Therefore an elastic plastic finite element analysis must be carried out. By combining stress dataset and strain dataset for each increment elastic plastic block was generated. The inbuilt fe-safe material database for S316 stainless steel is used for fatigue simulation and the surface finish was assumed as mirror polished ($k_t=1$).

Brown-miller equation with morrow’s mean stress correlation was selected as the algorithm. Although the loading is uniaxial, uniaxial strain life equations cannot be used in fe-safe for 2D or 3D objects as stress and strains are not uniaxial.

Fe-safe uses “critical plane” method to identify the most damaging plane by using brown miller equation for planes at 10º intervals between 0º and 180º in the surface of the component. (Fe-safe, 2002) The fatigue life variation in the specimen is shown below.

![Figure 5. Fe-safe simulation of 1.77% strain Log (Life-Repeats) of the specimen](image)

### 4. COMPARISON OF RESULTS

Two sets of simulations were performed using an elastic plastic block but varying the surface finish to observe the sensitivity. Another simulation was performed with an elastic block. Table 2 compares the results obtained for the simulations against the experimental results obtained by (Zhou, et al., 2008).

<table>
<thead>
<tr>
<th>Strain amplitude (%)</th>
<th>Experimental result (Zhou, et al., 2008)</th>
<th>Number of reversals to failure (2NF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain amplitude (%)</td>
<td>Experimental result (Zhou, et al., 2008)</td>
<td>Abaqus and fe-safe simulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Using Elastic Plastic block</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mirror polished</td>
</tr>
<tr>
<td>0.99</td>
<td>1322</td>
<td>1198</td>
</tr>
<tr>
<td>1.28</td>
<td>791</td>
<td>616</td>
</tr>
<tr>
<td>1.5</td>
<td>576</td>
<td>411</td>
</tr>
<tr>
<td>1.77</td>
<td>413</td>
<td>292</td>
</tr>
<tr>
<td>2.1</td>
<td>293</td>
<td>216</td>
</tr>
<tr>
<td>2.4</td>
<td>225</td>
<td>162</td>
</tr>
</tbody>
</table>

Table 2 Comparison of fatigue life results
As shown in the Figure, the mirror polished surface finish which is the actual condition in the original test gave the closest behaviour to tested results. The simulation is within 25% range of the actual values. The original experimental results indicate that there is a 10%-20% variation of the experimental curve presented here. Therefore the simulation results is in an acceptable range.

The rough surface finish that is present in type 316 rebars (Kalpakjian, 6th edition) will give fatigue limits in the range of half that was for mirror polished. This indicates the surface finish is a primary factor for fatigue life of a material. As shown in Table 2, the simulation with an elastic block with Neuber’s rule gives large fatigue lives which are not acceptable. The reason as explained in 3.4 is Neuber’s rule being valid only when stress redistribution is insignificant. In this experiment, the whole central region of the specimen is subjected to plastic stresses. Therefore elastic-plastic stress block method is preferred.

5. CONCLUSIONS

- Abaqus and fe-safe were successfully coupled to predict the uni-axial fatigue behavior of a stainless steel specimen.
- Prediction of cyclic loading behavior depends on the chosen hardening model. Nonlinear kinematic hardening model was chosen to generate the stabilized cyclic response.
- Surface finish is a sensitive factor for the fatigue life. Exact surface roughness should be estimated in order for better predictions.
- Neuber’s rule with elastic block is suitable for low cycle fatigue only when stress redistribution is not significant. Elastic-plastic analysis should be performed in fe-safe when the stress redistribution is significant.

6. REFERENCES

Abaqus, 2013. documentation: Simula.