Estimation of Fatigue Life of Steel Masts using Finite Element Modelling

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ABSTRACT: Fatigue is an important design consideration for tall steel structures. Accurate prediction of fatigue endurance is essential to design the elements subjected to wind and earthquake induced 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 demonstrates successful coupling of Abaqus/FEA and fe-safe software in predicting the uniaxial and multiaxial fatigue behaviour of steel specimens. The simulated results were verified against experimental results available in literature. The verified simulation technique was used to examine the fatigue life of a64 m tall steel mastlocated on top of a 285m tall tower. Sensitivity of different fatigue inducing properties such as fatigue analysis method, surface finish and plate thickness on fatigue endurance was studied.

1 INTRODUCTION

A material can fail well below its monotonic strength 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.

Tall steel structures are subjected dynamic loading such as wind and earthquake induced loading during their lifespan. The wind-induced loadings are very significant at greater heights. These tall structures are often slender hence; they are sensitive to dynamic loading. Therefore, dynamic stresses on the elements of those structures are significant.

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_{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 and Mendis,2000). Therefore, fatigue modelling using 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 etc. can be included for accurate estimations.

2 OBJECTIVE

The main objective of this research is to verify the fatigue simulation techniques used in analysis using finite element software and then use those techniques to check the fatigue limits of fatigue prone details of tall steel structures.

3 THE CONCEPT

The concept of this research is development of finite element models and importing stress datasets to fatigue estimating software to predict the fatigue endurance of structures. This is a more efficient method compared to laboratory testing and use of codes of practices.

The fatigue simulations have been performed successfully in the literature for low cycle and high cycle fatigue using Abaqus and fe-safe software, but mostly for a selected strain amplitude levels (Glodež and Knez, 2007) (Staudingerand Reiter, 1997). The first verification test in this research is done for uniaxial fatigue for different strain amplitudes and the second verification test is done for a selected strain amplitude to verify multiaxial fatigue. The verified simulation techniques were applied to the tower mast to check its fatigue endurance.

4 FATIGUE ANALYSIS THEORY

Fatigue endurance under uniaxial fatigue, for different constant amplitude strain levels are presented in the form of S-N curves. S-N curves are

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widely used to estimate fatigue damage by generalizing them for different shapes, different loading histories and different materials.

Generalization of constant strain amplitude test data for complex loading histories is done using Miners rule together with Rain-flow cycle counting method. Generalization for shape, mean stress and other factors are done through the correction factors (Fe-safe, 2002).

4.1 *Uniaxial Fatigue*

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

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

Where $\Delta\varepsilon$ is the applied strain range and 2Nf is the number of reversals to failure. b and c are fatigue strength exponent and fatigue ductility exponent, respectively. σ'_f and ε'_f are fatigue strength coefficient and fatigue ductility coefficient, respectively (Fe-safe, 2002).

4.2 *Multi Axial Fatigue*

Use of uniaxial formulae for multiaxial fatigue may overestimate the fatigue life. Brown Miller equation with Morrow's mean stress correlation can be expressed as,

$$\frac{\Delta\gamma_{max}}{2} + \frac{\Delta\varepsilon_n}{2} = 1.65\,\frac{(\sigma'_f - \sigma_{n,m})}{E}(2N_f)^b + 1.75\,\varepsilon'_f\,(2N_f)^c$$

where $\Delta\gamma_{max}$ is the maximum shear strain, $\Delta\varepsilon_n$ is the normal strain range and $\sigma_{n,m}$ is the mean normal stress on the plane (Fe-safe, 2002).

5 VERIFICATION OF FEA SIMULATIONS

5.1 *Uni-Axial fatigue simulation*

An experimental study performed by Zhou, et al., 2008 on the low cycle fatigue of stainless steel reinforcement bar specimens is simulated using Abaqus FEA and fe-safe software.

5.1.1 *Fatigue simulation*

A non-linear kinematic hardening model was used for the analysis as described in Staudingerand Reiter, 1997. 3D20R solid elements with varying mesh density were used to perform static general analysis neglecting the geometric nonlinearity. Fig. 1 shows the finite element model and Table 1 presents the material properties used in the simulation.

Table 1 Material properties uniaxial test specimen

Mechanical Properties	Cyclic Elastic properties (Zhou, et al., 2008)	
	Young's modulus (MPa)	Poisson's ratio
	199817	0.33
	Cyclic Plastic properties (J.Shita, et al., 2013)	
	Yield stress(MPa)	Plastic strain
	270	0
	300	0.0025
	330	0.0075
	350	0.0125
	370	0.0175
	400	0.04
Fatigue Properties (Fe-safe M.D., 2014)	b	-0.0835
	c	-0.5142
	ε_f'	0.476
	σf'	703.4

Fe-safe fatigue analysis for elasto-plastic range can be performed, by using an elastic block with Neuber's rule or by using an elastic plastic block. Sensitivity for both methods of analysis and for different surface finishes have been examined.

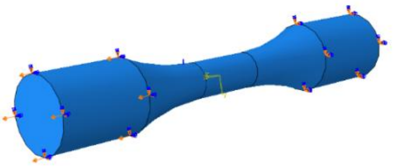

Fig. 1 Finite element model of uniaxial test specimen

5.1.2 *Comparison of results*

Table 2 compares the predicted number of cycles to failure with different surface parameters and fatigue analysis methods.

Table 2 Comparison of number of cycles to failure

	Number of reversals to failure (2Nf)			
Strain amplitude (%)	Experimental result (Zhou, et al., 2008)	Abaqus and fe-safe simulation		
		Using Elastic Plastic block		Elasticblockwith Neuber's rule
		Mirror polished	Rough(Ra-2um)	Mirror polished
0.99	1322	1198	552	54487
1.28	791	616	336	42369
1.5	576	411	225	35483
1.77	413	292	162	31438
2.1	293	216	120	28763
2.4	225	162	90	27064

It is clear that the elastic block method has given erroneous results. The reason is that Neuber's rule is valid only when stress redistribution is insignificant. Out of the elastic plastic method results, mirror polished surface finish, which is the actual condition in the original tested specimen, gave the closest results. The rough surface finish that is present in type 316 rebars(Kalpakjian, 2006)have given fatigue limits in the range of half that was for mirror polished. This shows that surface finish is very sensitive parameter and according to Kalpakjian (2006)surface finish of single finishing technique has a large range. Therefore it is important to use the correct surface roughness for accurate predictions.

5.2 *Multi-Axial Fatigue Simulation*

Glodež and Knez, 2007 have conducted an experimental study on the fatigue behavior of high strength steel crawler crane arms. Table 3 and Fig. 2 present material properties and finite element model, respectively.

Table 3Material properties of crawler crane arm

Density	7850 kgm^{-3}
Cyclic elastic properties	(Hachim, et al., sep 2012)
Young's modulus	200Gpa
Poisson's ratio	0.3
Yield strength	372Nm^{-2}
BS 5950-1:2000:Table 9 (40mm<thickness<63mm)	335Nm^{-2}
Fatigue properties BS 4360 G50A((Fe-safe M.D., 2014)	
b	-0.122
c	-0.598
ε_f'	0.182
σf'	1081

5.2.1 *Fatigue simulation of crawler crane arm*

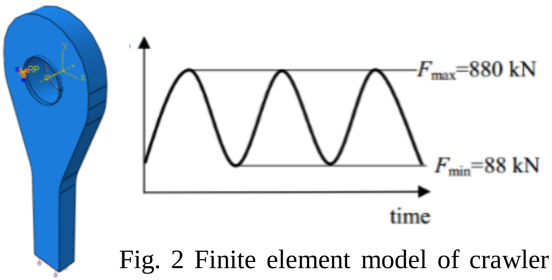

Fig. 2 Finite element model of crawler crane arm and applied loading curve

Non-linear kinematic hardening model (Abaqus, 2013) was used for the analysis. C3D8 elements with varying mesh densities were used to perform dynamic explicit analysis with geometric nonlinearity.

5.2.2 *Comparison of results*

Table 4 compares experimental results with simulations.

Table 4Comparison of simulation and experiments

Experimental Results				FEA results
Test 1	Test 2	Test 3	Test 4	
38029	26727	24795	29036	29979

Finite element analysis results yields a closer relationship with experimental results. Hence, the simulation techniques and idealizations can be accepted for multi axial fatigue.

6 CASE STUDY

The case study was carried out on a steel mast on top of a 285m tall tower. It is a 64.1m tall tubular steel mast with few openings near the base. The material near the opening is vulnerable to fatigue due to high stresses and hence that region is considered for this study.

Table 5Material properties of steel mast

	Cyclic Elastic properties	
	Young's modulus (MPa)	Poisson's ratio
Mechanical Properties (Glodež and Knez, 2007)	194889	0.3
	Cyclic Plastic properties	
	Yield stress(MPa)	Plastic strain
	875	0
	1000	0.015
	1100	0.0766
Fatigue Properties (Glodež and Knez, 2007)	b	-0.0997
	c	-0.978
	ε_f'	9.93
	σf'	2076Mpa

Table 5 presents the material properties and Fig.3 shows the finite element model.

6.1 *Fatigue Simulation of Steel Mast*

Square (0.89m edge length) and circular (1m diameter) openings of same area and different plate thicknesses (30mm and 40mm) were analyzed. Abaqus standard was used with general static analysis neglecting the geometric nonlinearity.

S8R elements with finer mesh density around the opening were used.

It was found that the gust factor anddesign wind pressure is 1.77 kN/m^{2}and 2.6kN/m^2, respectively according to AS1170.2, 1989.Elastic fatigue analysis was performed. The surface finish of the steel plates are assumed as fine machined (4< Ra< 16).

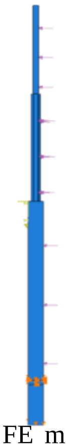

Fig. 3 FE model of the mast

6.1.1 *Comparison of Results*

Fig. 4 compares the stress variation and fatigue endurance of two openings. Table 6 presents the number of cycles to failure. Although corners of square openings create higher stress concentrations, the bending stress increase due to larger opening dimension in the center level of circular opening.

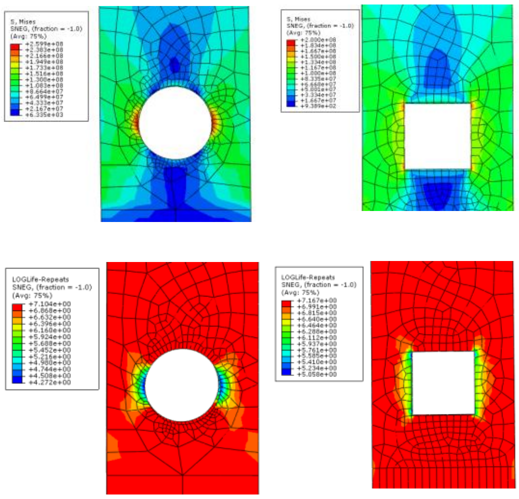

Fig. 4 Variation of Stress(top) and fatigue endurance(bottom) in square and circular openings

Table 6Number of Reversals to failure (2Nf)

Opening shape	Thickness 30mm	Thickness 40mm
Circular	18,367	113,161
Rectangular	60,051	426,693

Although the maximum stress around the opening was reduced by the same percentage (33%) as the plate thickness increased, the endurance has increased by around 500-600% in both shapes. This indicates the importance of adopting stiffeners.

The endurance in the square opening is almost 230-270% higher than in the circular opening. This indicates the importance of choosing a proper shape for openings. If the corners of the rectangular opening are smoothed more endurance can be expected.

7 CONCLUSIONS

The simulations done to verify uniaxial fatigue and multi-axial fatigue indicates that finite element software can be used to predict fatigue endurance. However, high sensitivity to material model chosen as explained in the Section 5.1.1 indicates it is very important to carefully choose correct material behaviour. On the other hand, fatigue is highly sensitive to the surface finish but surface finish has a large range for even the same machining process. Fatigue properties of a material is not as constant as monotonic properties. Hence, it is advisable to perform fatigue tests for the exact material to be used and use those properties for the analysis.

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