Benchmark Problems in Multiaxial Fatigue

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ABSTRACT

Fatigue analysis software packages range from the simplest to most complex both in terms of fatigue theories and material properties. In this paper, several of these commercial packages are employed to reanalyze a benchmark dataset reported at the first multiaxial fatigue symposium held in 1982. Surprisingly, our calculations show that all of the software evaluated gives about the same results. Even more surprising we found that the modern fatigue software was no better than the calculations done 30 years ago. But today, an inexperienced first year graduate student can use modern software to produce the same quality of fatigue assessment as an experienced PhD student 30 years ago.

INTRODUCTION

The first International Symposium on Biaxial/Multiaxial fatigue was held in 1982. A few excerpts from the printed volume, ASTM STP 853, that summarizes the symposium held 30 years ago are worth noting.

> *… Thus stresses should be taken into consideration by the designer, and it is important to note that material data generated in laboratories … cannot be used in practice without recourse to some multiaxial criterion …*
> *… this volume shows that significant progress has been achieved towards predicting finite fatigue life behavior, and it should provide a useful aid in interpreting failures and understanding the mechanics of fatigue …*
> *… Life prediction techniques have been broadly based on crack development concepts, and new methods are compared with the older criteria and current design codes, showing that the new methods have much potential …*

Has this potential been realized for the designer? Software tools are readily available for the designer. Many finite element codes have a simple drop down menu for multiaxial fatigue analysis. Special purpose commercial fatigue codes are also in widespread use.

A fatigue estimate is only a few mouse clicks away. But how well do they work? To answer this question we look at a benchmark data set first described in the 1982 symposium in a paper “A Fatigue Test System for a Notched Shaft in Combined Bending and Torsion“[1] .

In this paper we compare the results of modern software tools with the original life calculations from the paper “Fatigue Life Estimates for a Simple Notched Component Under Biaxial Loading”[2] done 30 years ago. Five software packages, Pro/E, Solidworks, Ansys Workbench, eFatigue and nCode’s DesignLife were used to compute the fatigue lives for 75 combined bending and torsion tests of the notched shaft. Three sets of calculations were done by a first year graduate student with limited experience in fatigue analysis software. These results are compared with the results from an experienced designer from an automotive company. Results from the senior author’s eFatigue website are also included.

BENCHMARK DATA SET

In 1982 the Society of Automotive Engineers (SAE) Fatigue Design and Evaluation Committee established a testing program to provide experimental data for assessing the reliability of multiaxial design procedures and to stimulate the development of improved analytical methods. A simple notched shaft, Fig. 1, that simulated a spindle in a farm tractor, was selected as the test specimen which was made from normalized SAE 1045 steel. Experiments were preformed by applying cyclic bending and torsion loads to the shaft. Fatigue life was defined as the formation of a crack 1mm long on the surface which was detected ultrasonicly. Here, we only consider the fully reversed loading tests. Details of the benchmark data set can be found in reference 3. A summary can also be found on the eFatigue website.

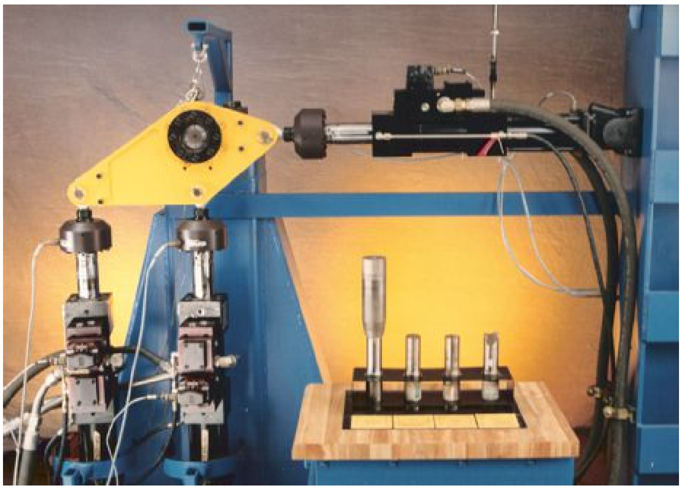

Figure 1. SAE notched shaft.

FATIGUE ANALYSIS SOFTWARE

A brief summary of the fatigue theories and strategies employed by the various software packages used to compute fatigue lives is given below. A common feature of all of the analysis is that they used what may be termed the strain-life method. Commonality ends there. They all used different notch rules and fatigue damage models.

Fash et.al.

1. nonlinear ABAQUS model for stresses and strains
2. uniaxial strain life curve
3. Brown-Miller[4] damage model

Solidworks

1. elastic fea model for stresses
2. pseudo stress-life curve obtained from uniaxial Neubers rule[5] and uniaxial strain life curve
3. equivalent stress with uniaxial pseudo stress-life curve

Pro Mechanica

1. elastic fea model for stresses
2. uniaxial strain-life curve derived from uniform material law[6]
3. notch strains from Hoffman-Seeger[7] or Klann-Tipton-Cordes[8] whichever is greater
4. equivalent strain in Smith-Watson-Topper[9] or Morrow[10] which ever is most damaging

Ansys Workbench

1. elastic fea model for stresses
2. pseudo stress-life curve obtained from uniaxial Neubers rule and uniaxial strain life curve
3. equivalent stress with uniaxial pseudo stress-life curve

DesignLife

1. elastic ABAQUS model
2. uniaxial strain-life curve
3. uniaxial Neubers rule from equivalent stress
4. Smith-Watson-Topper with equivalent strain

eFatigue

1. elastic Ansys model
2. uniaxial strain-life curve
3. Koettgen-Barkey-Socie[11] for 3D stress and strain tensors
4. critical distance for gradient effects
5. Fatemi-Socie[12] or Smith-Watson-Topper which ever is most damaging

ANALYTICAL RESULTS

Results for the in-phase tests are shown in Fig. 2. The vertical axis is the ratio of experimental life / analytical life so that a number greater than 1 is conservative. The analytical life is plotted on the horizontal axis. This format was selected over the more traditional 45° experimental/analytical plot because a designer computes an analytical life and wishes to know how it might compare to experiments. As a point of reference, the solid symbols represent the original calculations from Fash et.al. in 1982. Here we see that the scatter for all of the calculations is within a factor of +/- 10. This is surprising since most published papers claim accuracy within a factor of 2 or 3.

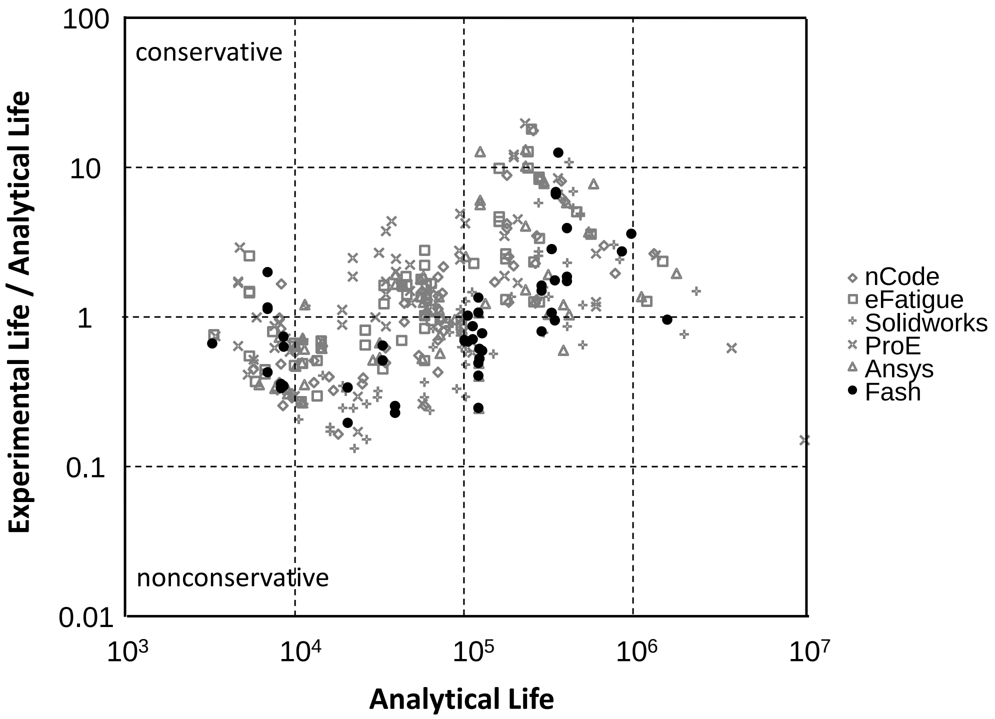

Figure 2. Analytical results for in-phase loading.

Results for out-of-phase tests are shown in Fig. 3. Only eFatigue and Design Life were employed for these loadings since none of the simplified analysis software has the capability to analyse nonproportional loading.

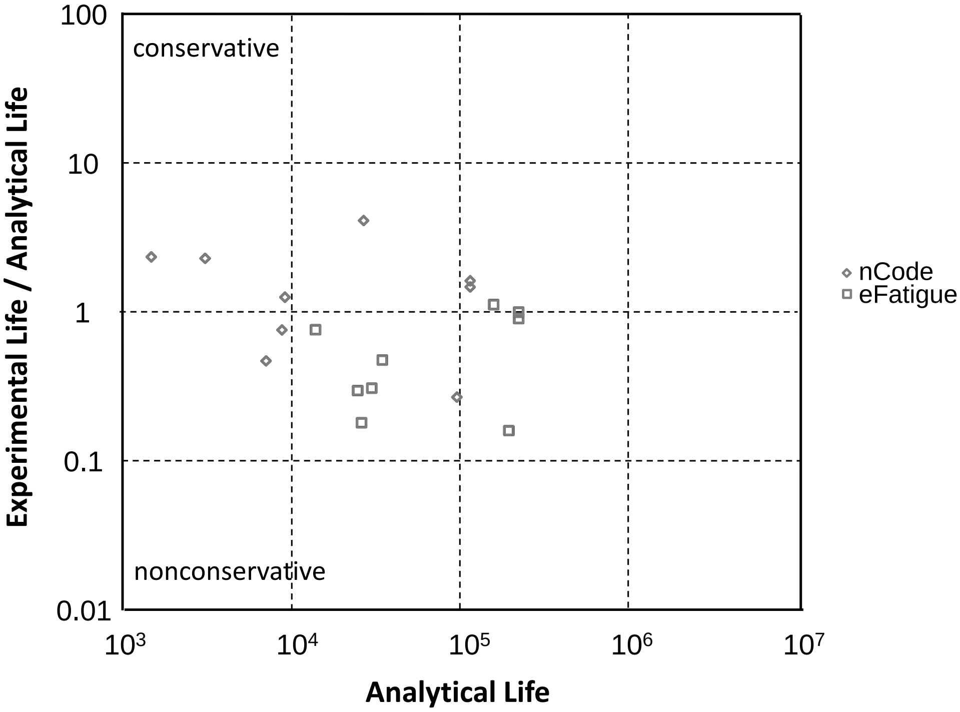

Figure 3. Analytical results for 90 deg out-of-phase loading.

DISCUSSION

Our purpose here is not to directly compare the results from one software package with another to conclude which one is better or more accurate. The more advanced packages have a number of options that allow someone to fine tune the analysis for any dataset and an experienced user can sometimes make the estimates better than those presented here, particularly if the test results are known. Rather our focus was on how well someone would be expected to produce an accurate life estimate, without knowing the answer.

The inexperienced student (Utagawa) used the default features available in Solidworks, Pro Mechanica, and Ansys Workbench with some reasonable choices such as using Mises rather than principal stress. The experienced industrial fatigue analyst used one of the most sophisticated software packages, nCode's Design Life, with the guidelines for analysis that are used in their company. Finally, a fatigue researcher (Socie) used the most sophisticated algorithms in eFatigue. Although there is limited data, there is no substantial difference in the accuracy shown in Fig. 2 and Fig. 3 for out-of-phase loading. One could easily argue that all of the data in Fig. 2 falls within the same scatter band and that everyone did equally well and none did better that the early work of Fash. There is one significant and important difference, the modern analysis took a few hours rather than the year Fash needed to do all the analysis.

Results from Fig. 2 are plotted in a cumulative distribution diagram in Fig. 4. From this figure we may conclude that there is a 99% chance to be within a factor of 10 in fatigue life. Three standard deviations would be about a factor of 20 in fatigue life.

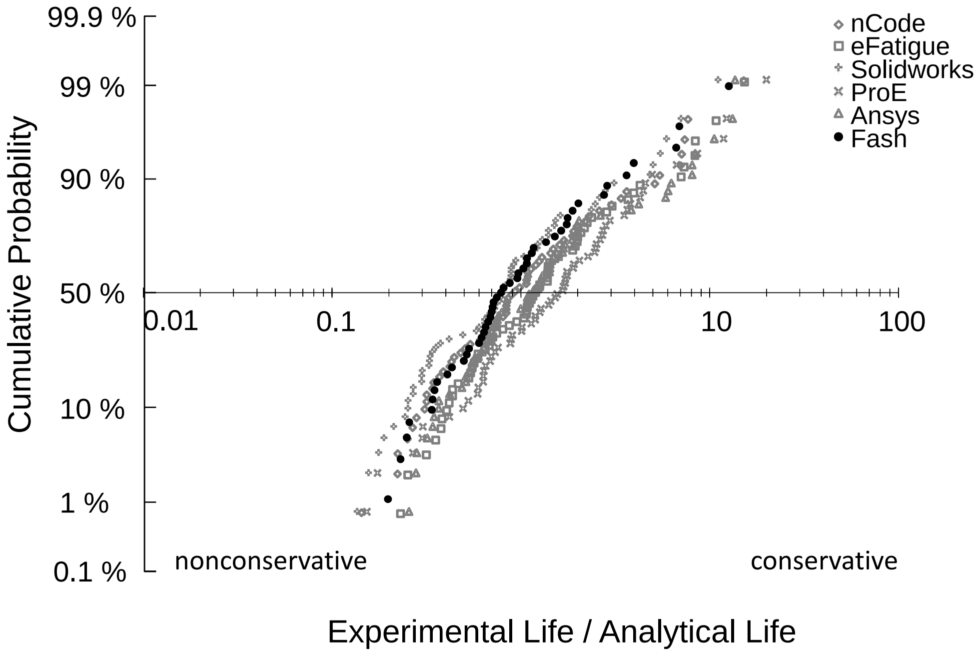

Figure 4. Cumulative probability distribution for in-phase loading.

Why are all the datasets essentially the same and why is there so much scatter in the results? Finite element results for stresses varied by about 3% between all the different finite element models for all load cases. Although the details are not reported here, we found that the results could change by at most a factor of 2 when the element type and size were changed. This may explain why the results are similar but does not provide an explination for the large amount of scatter observed.

There is always some scatter in the material fatigue data. Reference 3 also contains a number of combined loading tests on tubular specimens. The baseline uniaxial material constants used to analyse the shaft were used to analyse the tubular specimen data. The Fatemi-Socie damage model was employed to compute the fatigue lives. Results are shown in Fig. 5. There is a 99% chance to be within a factor of 2 not 10 in fatigue life! We conclude that our ability to model real components with complex stress gradients and stress states is poor when compared to smooth laboratory specimens.

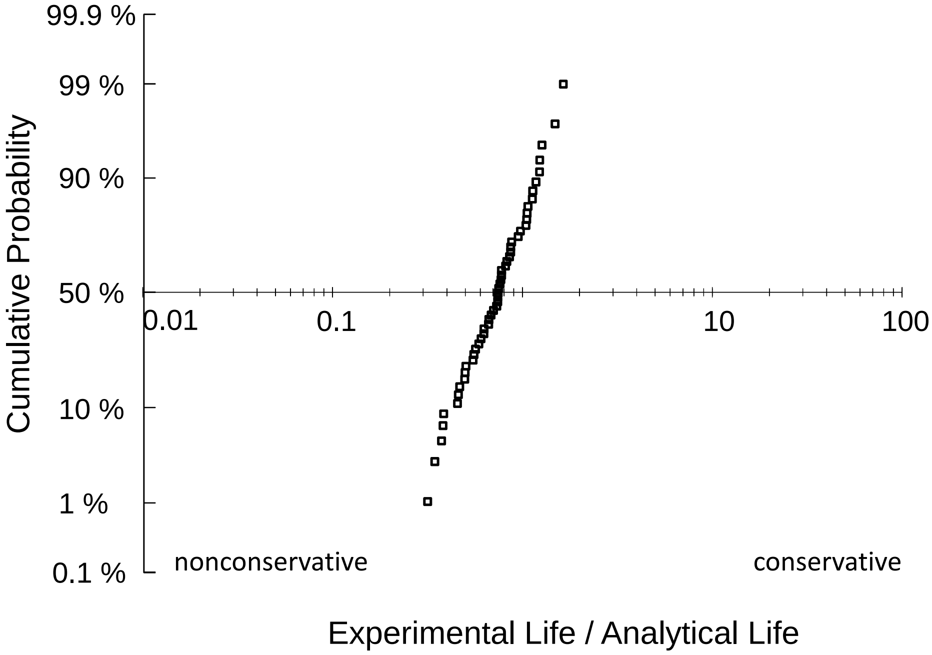

Figure 5. Cumulative probability distribution for tubular specimens.

SUMMARY

Here we make a bold statement based on our experience with many datasets. It is relatively easy to make fatigue life estimates on a cylindrical tube, made from a common ductile material, with a ground surface finish, subjected to completely reversed constant amplitude sinusoidal loading. In this case, anything reasonable will work. Unfortunately, many researchers choose these test conditions to validate their models. New and improved models can and should be evaluated under more complicated geometries and loading conditions.

REFERENCES

1. Downing, S.D., Galliart, D.R. (1985) In: *Multiaxial Fatigue,* ASTM STP 853 pp.24-32
2. Fash, J.W, Socie, D.F., McDowell, D.L. (1985) In: Multiaxial Fatigue, ASTM STP 853 pp.497-514
3. Socie, D.F. , Leese, G.L. (1989) Multiaxial Fatigue: Analysis and Experiments, Society of Automotive Engineers, AE-14
4. Brown M W, Miller K J (1973) *Proc Inst Mech Eng* **187**, 745-755
5. Neuber, H. (1961) *J of Applied Mechanics* **28**, 544-550
6. Bäumel, A., Jr., and Seeger, T. (1990) *Materials Data for Cyclic Loading*, Supplement 1, Elsevier Science Publishers, Amsterdam
7. Hoffmann, M., Seeger, T. (1985) *J of Eng Materials and Technology* **107**, 250-260

8. Klann, D.A., Tipton, S.M., Crodes, T.S. (1993) SAE paper 930401
9. Smith K. N., Watson P., Topper T.H. (1970) *J of Materials* **5**, 767-778
10. Morrow, J. (1968) In: *Fatigue Design Handbook* Society of Automotive Engineers, AE 4, pp 21–29.
11. Kottgen, V.B., M.E. Barkey, Socie, D.F. (1995) *Fatigue and Fracture of Engineering Materials and Structures* **18:4**, 981-1006
12. Fatemi, A., Socie, D.F. (1988) *Fatigue and Fracture Engineering Materials and Structures*, **11:3**, 149-166