Fatigue Analysis of an FEA Model of a Suspension Component, and Comparison with Experimental Data

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Summary:

The key features of modern local strain fatigue analysis are described. The analysis methods can now be applied successfully to complex components which produce non-proportional biaxial stresses at critical locations. Local strain fatigue analysis has been implemented as a software system for fatigue analysis of finite element models. The paper shows how fatigue analysis has been integrated into the design procedure at Simpson International UK Ltd, and shows how the analysis compares with component test results for both simple and complex loading. Fatigue analysis from finite element models is a recent development, and there is much to learn about its routine application in engineering design. However, very reliable predictions of the locations of potential fatigue cracks can be made, and the correlation between calculated fatigue lives and test results is extremely encouraging.

Keywords:
Multiaxial fatigue, biaxial fatigue, local strain fatigue, low cycle fatigue, finite element models, vehicle components, suspension components, validation.

1 INTRODUCTION

Simpson International offers complete design and development services for wheel-end components and assemblies to automotive and truck manufacturers throughout the world. As a full service supplier, SI offers a quick response, design and engineering support, rapid prototype capabilities, static / fatigue testing, simultaneous engineering / launch, and material development and analysis. An essential part of this service is the ability to develop designs quickly using state-of-the-art finite element analysis, computer-based fatigue analysis, and realistic testing of the final design. This paper describes the fatigue analysis techniques used by Simpson International and shows how they are integrated into the design procedure.

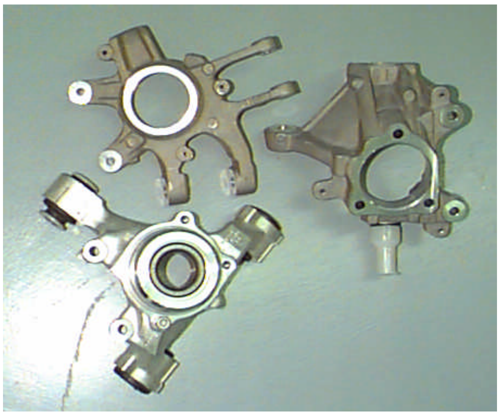

Figure 1. Examples from Simpson Industries product range.

2 THEORETICAL BACKGROUND

2.1 Fatigue analysis for uniaxial stresses.

The theories for fatigue analysis based on local surface strains have been developed from the 1950's. A major feature of local strain fatigue is that fatigue lives to crack initiation can be calculated. This is of increasing importance as more emphasis is being placed on product safety and product liability legislation, and as a result the traditional approach to 'total life' fatigue based on stress-life curves is becoming much less relevant.

Local strain fatigue techniques were first applied to the analysis of simple strain gauges in the late 1970's [1]. Simple cyclic plasticity models were developed to estimate elastic-plastic stresses from the measured strains, so that the effects of mean stress could be included. The original theories were developed for uniaxial stress conditions. However, during the 1980's it became increasingly apparent that biaxial stresses were produced at critical locations in real engineering components, and that fatigue life estimates based on an assumption of uniaxial stress would produce significant errors. Devlukia and Davies [2], and Tipton and Fash [3] were among the many authors who documented such errors.

2.2 Fatigue analysis for biaxial stresses.

McDiarmid [4] proposed that for high cycle fatigue successful life estimates for biaxial stress conditions could be made using combinations of axial and shear stresses. Brown and Miller [5] extended this work into low cycle fatigue by using combinations of axial and shear strains. These methods have been very successful in practical fatigue analysis. Mroz [6] proposed a multi-surface kinematic hardening model for variable amplitude cyclic loading which allowed stresses to be calculated from the measured strains. Lamba [7] later proposed a two surface model and this has been the basis for several general cyclic plasticity models.

Bannantine and Socie [8] synthesised these methods into a unified multiaxial fatigue life estimation system for strain gauge rosettes, using critical plane procedures. For many ductile metals, fatigue cracks initiate on planes which experience the maximum shear strain amplitude. The normal strain and the associated stresses are modifiers. It has been shown that for cracks which originate from the surface, three basic planes are required (Figure 2), one perpendicular to the surface and two at 45^{o} to the surface. For proportional stresses one of these planes will be the critical plane. For non-proportional stresses, where the principal stresses change direction as well as change their magnitude, each of these planes is rotated through 180^o in small steps, typically 5^o or 10^o . The time history of shear and normal strain and the associated stresses are calculated for each plane and for each step through 180^o. The fatigue damage on the most damaged plane is determined, using an appropriate fatigue damage model. Applying the Brown-Miller combined shear and normal strain parameter in critical plane analysis has proved very successful. Various mean stress corrections have been proposed for the Brown-Miller parameter, one of the most recent being that of Chu, Conle and Hubner [9]. For very high strength steels and some cast irons, fatigue lives are calculated using axial strains, again with a critical plane procedure for non-proportional stresses.

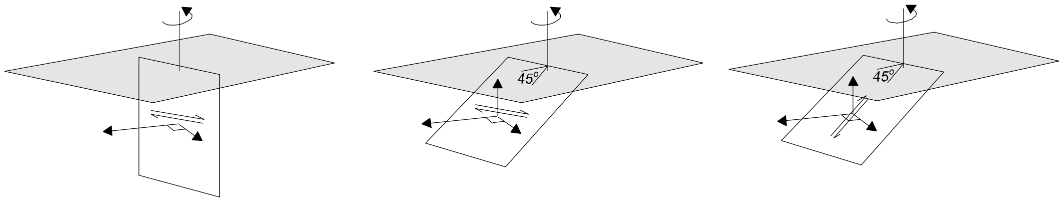

Figure 2 The three planes used in critical plane analysis.
The surface of the component is shown shaded.

2.3 Fatigue analysis from finite element models

In 1991 Devlukia, Draper and McDiarmid [10] put forward a proposal to apply these techniques to the analysis of finite element models. A £650,000 ($1million) research and development program was submitted to the UK Government, who offered substantial funding for an integrated program of research, software development and validation testing. The validation testing was carried out by Rover Cars at the Gaydon Technical Centre in England. The project was completed in 1996, and the software was subsequently developed into a commercial suite of software *fe-safe* by Safe Technology Limited [11]. The ability to analyse high temperature fatigue, creep fatigue, cast iron components and probability of failure were added subsequently. Current research is adding the capability to include the effects of press-forming sheet components [12].

Considerations of cost and processing speed mean that many designers wish to use an elastic finite element model as a basis for fatigue design. Glinka [13], Barkey [14] and others have proposed methods of calculating cyclic elastic-plastic stress-strains from the elastic FEA stresses.

2.4 Effects of stress gradient and notch sensitivity.

There is much experimental evidence from fatigue testing carried out in the middle of the last century showing that stress gradients have an important effect on the total fatigue life of a component. This is particularly evident on smooth test specimens, but the effect seems to be less significant at geometric notches in real components. Local strain fatigue analysis from strains measured in notches has shown good correlation even though the effects of stress gradient are ignored.

Stress gradients have also been used in an attempt to explain the effect of notch sensitivity. Traditional methods used the elastic stress concentration factor for a notch, combined with an algorithm to allow for the effects of stress gradient [15,16,17]. In general these methods have had mixed success. Finite element analysis provides surface strains on the model, but for real engineering components it is very difficult to determine the stress concentration factor at a notch. Taylor [18] has proposed a very successful method of estimating the effects of notch sensitivity on the fatigue limit stress, using the stress gradient from the finite element model and the threshold crack tip stress intensity factor. Taylor's method is based on the observation that for a notch of specified depth, the fatigue limit stress reduces as the notch gets sharper, i.e. as the stress concentration factor increases, and that for many ductile metals, a minimum value of fatigue limit stress occurs. Further increasing the stress concentration factor by sharpening the notch produces no further reduction in fatigue strength (Figure 3). FEA surface stresses or strains calculated in the notch can therefore be used for blunt notches, but will give conservative life estimates for sharper notches. Taylor used the life to a 2mm crack as the fatigue life.

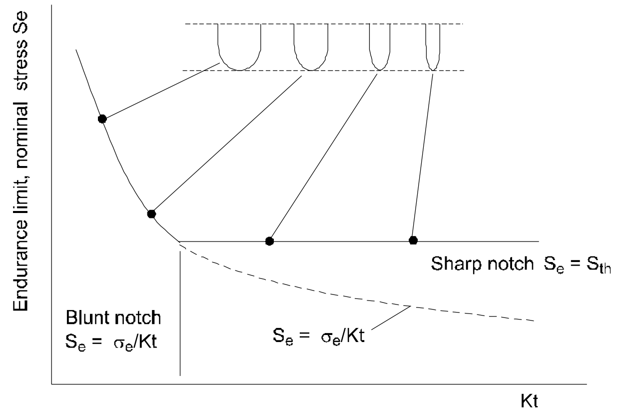

Figure 3 Relationship between endurance limit stress
and the stress concentration factor Kt
(σ_e is the smooth specimen endurance limit stress,
S_{th} is the threshold stress for non-propagating cracks))

Frost and Dugdale [19] and Frost [20], using test data on flat plate and round bar specimens in aluminium alloy and steel materials, have shown that if fatigue life to first crack initiation is considered, then the fatigue strength reduces with increasing stress concentration with no limiting value (Figure 4). It seems therefore that crack initiation may be determined by surface strains and stresses with no significant stress gradient effect, at least for the geometric features usually present in engineering design. However, in the high stress gradients which are present at sharper notches the crack may propagate into a region of low stress where the stress intensity factor at the crack tip is less than the non-propagating value S_{th}, and as a result the crack ceases to grow.

Use of stress gradients may therefore imply that the designer is no longer designing to prevent crack initiation, but instead is relying on a calculation that the cracks will initiate but not propagate. This may be an unsafe assumption in some complex components where crack growth may be accelerated by load redistribution.

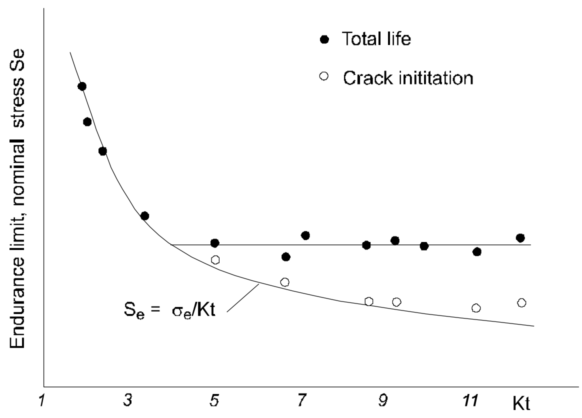

Figure 4 Relationship between endurance limit stress
and the stress concentration factor Kt for crack initiation and total life
(σ_e is the smooth specimen endurance limit stress)

2.5 Miner's rule and the endurance limit.

Conle and Topper [21], and Topper and co-authors [22] have shown that the constant amplitude endurance limit does not apply to the analysis of real service loading if some cycles in the loading exceed the constant amplitude endurance limit stress amplitude. For finite life design the larger cycles in the loading cause the endurance limit stress to be reduced significantly, with the result that small cycles contribute to the fatigue damage process. This effect has been included in many of the generic test signals derived by German industry (see for example the CARLOS car loading sequences), and must also be included in computer-based analysis.

3 VALIDATION EXAMPLES

Validation tests have compared the fatigue life estimates from *fe-safe* with test results from components. Simple and complex geometry with simple and complex loading histories have been used.

3.1 Simple fatigue test specimen.

Figure 5 shows the results of strain-controlled constant amplitude tests on an aluminium alloy at high temperature. The *fe-safe* calculation from an elastic FEA shows excellent correlation for high cycle fatigue. For low cycle fatigue, at 1000 cycles the calculated fatigue life is conservative by a factor of 3. This is a commonly observed phenomenon at such low fatigue lives in components where yielding occurs across the entire section.

For comparison, an elastic-plastic FEA analysis of the model was used as input into the *fe-safe* analysis, and the correlation with the test result was then excellent.

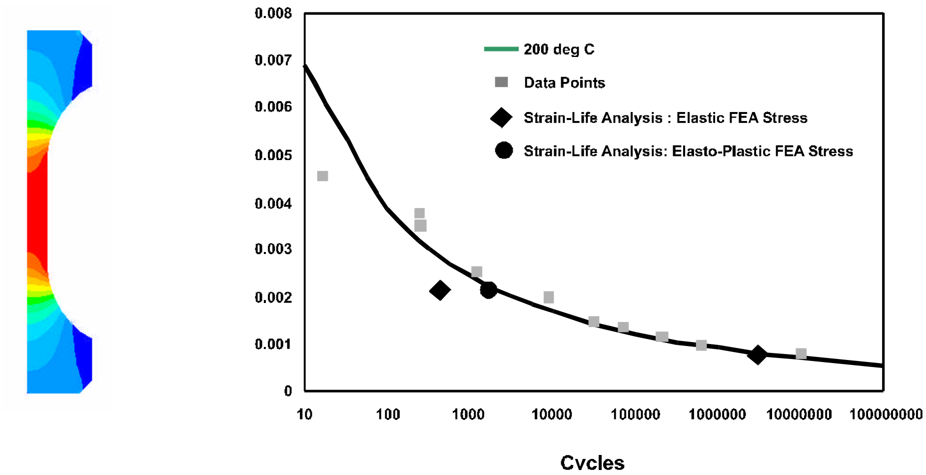

Figure 5 Comparison of test data
with calculated lives from elastic and elastic-plastic FE analysis

3.2 Steel component with a load-time history in one direction.

This component was analysed in *fe-safe* and compared with the results of fatigue testing. A scale factor was applied to the test loading to produce a failure. The correlation between the calculated life of 1631 repeats of the load history and the test life of 1650 repeats is extremely good.

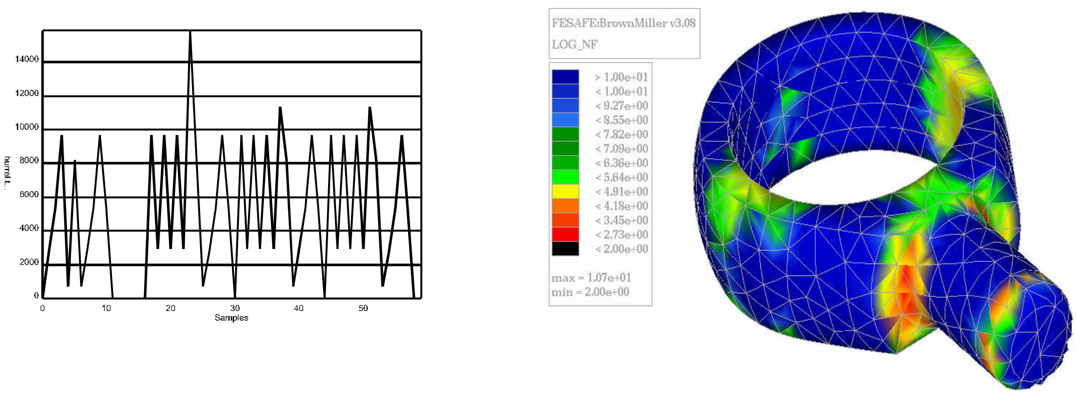

Figure 6. Loading history for accelerated testing (left) and fatigue life contours (right).
Test life : 1650 repeats of loading. Calculated life : 1631 repeats of loading.

The analysis used stresses from an elastic FEA; no allowance for the effect of stress gradient; a method of calculating cyclic elastic-plastic stress-strains based on biaxial Neuber/Glinka rules; and the Brown-Miller damage parameter with a mean stress correction. Fatigue lives were calculated for each node on the model, using averaged nodal stresses. Experience has shown that this is much more accurate than using stresses at integration points or at the element centroid.

3.3 Crank shaft test specimen.

In designing engine crank shafts the finite element analysis is used to generate stress solutions at 5^o angles of crank shaft rotation, through two or three revolutions of the crank shaft. The FEA analysis shows that the principal stresses change their orientation and magnitude during the load cycle applied to the crank shaft.

fe-safe uses the sequence of FEA analysis results to calculate the fatigue life at each node.
Tests on the crank shaft in combined bending and torsion showed that the crack did not initiate at the point of highest von Mises stress. This is an important result, because in the past FEA von Mises stress plots have been used to identify possible fatigue hot-spots. *fe-safe* correctly identified the critical location in the crank shaft, using a Brown-Miller fatigue analysis, and correlated well with test results.

A common theme from these validation exercises is that a uniaxial strain-life analysis using the maximum principal stress can fail to identify the critical location, for components where biaxial stresses and particularly non-proportional stresses are present at the critical locations.

4 ANALYSIS AND TESTING OF CAR SUSPENSION COMPONENTS.

4.1 Design procedure

The durability design procedure used by Simpson International is shown in Figure 7.

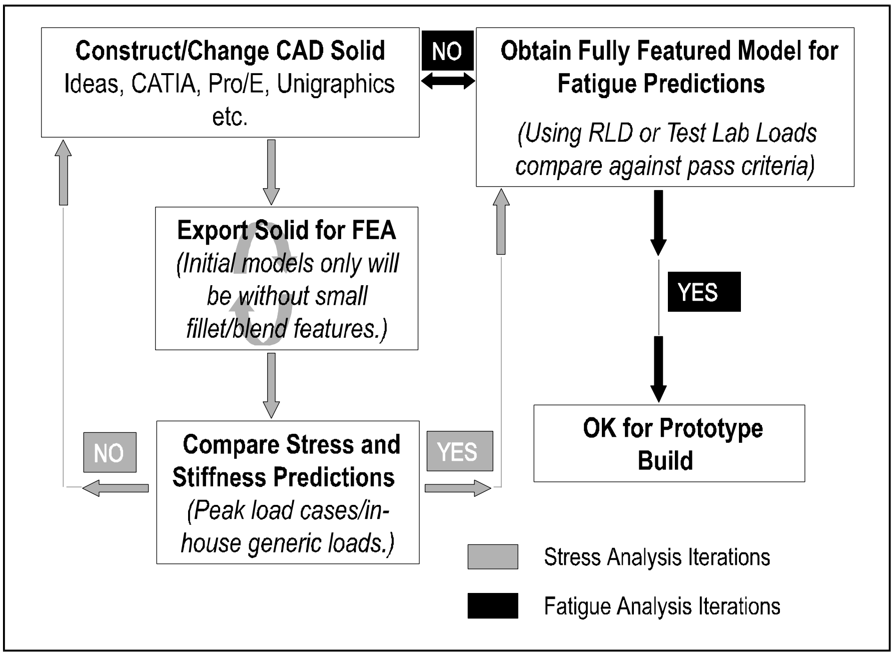

Figure 7 Example Procedure for Steering Knuckle CAE

In the computer-based fatigue analysis of the finite element model, the type of loading depends very much on the customer's requirements. Some companies specify a validation using simple sinusoidal loading, whereas other companies, such a Ford, require the application of measured time histories of vertical, braking and cornering forces on the tyre contact patch or wheel centre (Figure 8).

At present the test procedure uses a single actuator to apply the forces at the tyre contact patch, angled to produce a specific relationship between the three forces. *fe-safe* allows for different time histories to be applied in each direction, up to 4096 load histories of unlimited length.

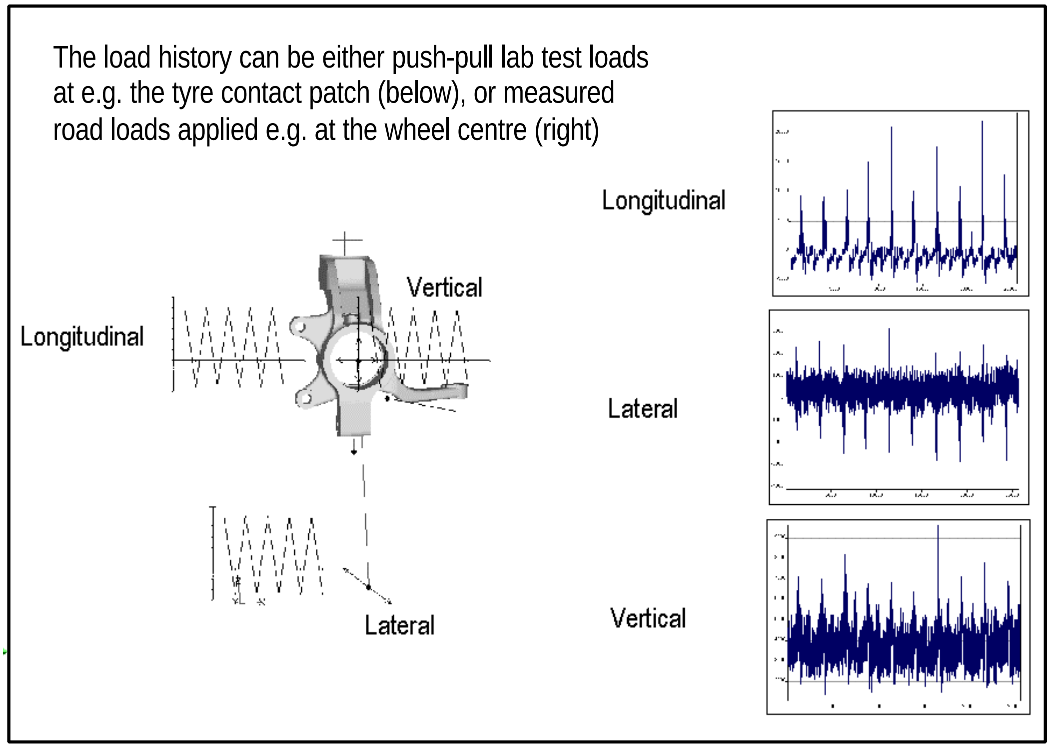

Figure 8. Application of force time histories.

The CAE procedure shown in Figure 7 uses a simple model for the initial design, without fillet radii or blend radii. The model is refined as the design is finalised. It is particularly important that a fully featured model is used for the fatigue validation. Typical mesh details for stress analysis and fatigue analysis are shown in Figure 9. Figure 10 shows a comparison of calculated fatigue lives for the initial and fully featured model. It is clear that too simple a mesh in the critical locations can give non-conservative life estimates.

Global Mesh Size - approx. 4mm	Global Mesh Size - approx. 4mm
Aspect Ratio - 5:1	Aspect Ratio - 5:1
Internal Growth - 1.5	Internal Growth - 1.5
Typical Number of nodes - approx. 65000	Typical Number of nodes - Up to 100000
Typical Number of Elements - approx. 35000	Typical Number of Elements - Up to 60000

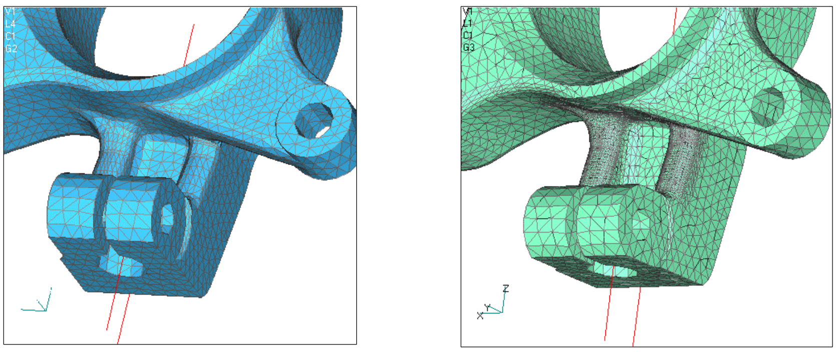

Figure 9. Typical mesh details for stress analysis – standard mesh (left) and fatigue analysis – refined mesh (right)

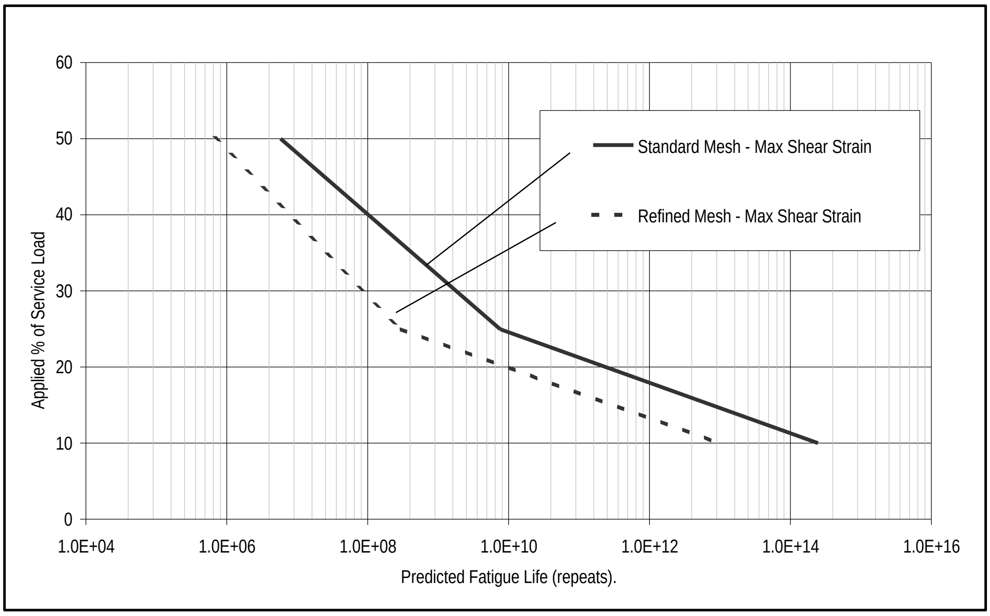

Figure 10 Effect of meshing on calculated fatigue life.
Fatigue lives calculated using maximum shear strain.

Once experience has been gained, the identification of fatigue hot-spots in complex components is very reliable. Figure 11 shows fatigue life contours for a prototype steering knuckle, calculated using *fe-safe* from an ABAQUS stress analysis.

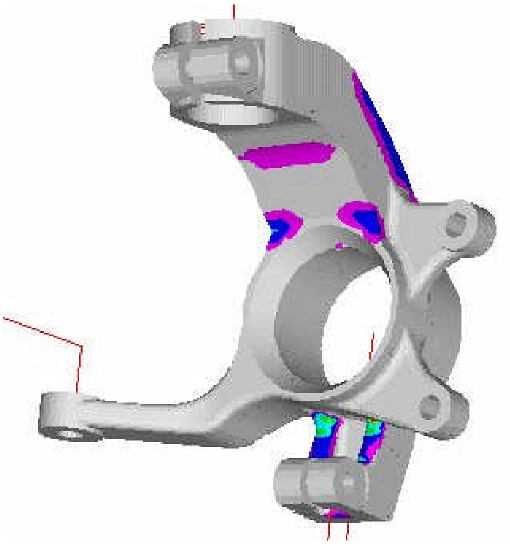

Figure 11 Fatigue life contours for a steering knuckle.

In one accelerated test on a prototype steering knuckle, the correlation between test life and *fe-safe* calculated life was :

test life to significant cracking : 41000 repeats of the load history
fe-safe life to crack initiation : 27000 repeats of the load history.

5 DISCUSSION

The theories presented in this paper have been applied in fatigue analysis software interfaced to finite element models. Fatigue and durability analysis from finite element models is a subject of continuing development, and there is much to be learned from the application of existing methods. In particular, the mesh density and perhaps the types of elements may influence the validity of the fatigue analysis.

New fatigue analysis algorithms are being proposed and assessed. The work by Dang Van and Papadopoulos on high cycle fatigue for multiaxial stresses is already implemented in software [11], and work on cyclic plasticity models and strain-life analysis is continuing (see for example [23]). However, with the methods currently available extremely good correlation between analysis and test is being obtained for a wide range of components and materials.

6 CONCLUSIONS

It has taken half a century to advance from the initial work on local strain fatigue to a practical analysis software tool for complex multiaxial fatigue analysis of finite element models. There is much to be learned from the practical application of existing methods, and much to be done to research and refine new methods. Notwithstanding this, practical tools now exist which can be integrated into the design process and used with confidence.

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