FATIGUE ANALYSIS OF A DIESEL PISTON FROM A FINITE ELEMENT MODEL

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ABSTRACT

Elastic finite element models were used to calculate the stresses in a diesel piston, for centrifugal forces, gas pressure, piston-to-cylinder contact and thermo-mechanical loading. A fatigue analysis superimposed the four loading conditions and calculated the fatigue life at each node on the model, adjusting the materials fatigue properties for the effects of nodal temperature. The identification of fatigue-critical locations, and the calculated fatigue lives, showed good agreement with test results.

THE COMPONENT

The component was a diesel engine piston. The loading consisted of centrifugal forces, gas pressure during firing, contact pressure between the piston and the cylinder liner, and thermal stresses caused by changes in engine temperature.

Each of these conditions was analysed separately in ABAQUS, using an elastic finite element analysis.

The stresses due to centrifugal forces were calculated for the maximum centrifugal force. The stresses caused by gas pressure were calculated for the maximum gas pressure. The time history of nodal forces from piston-to-cylinder contact was calculated using in-house software. The time-history of nodal stresses due to changes in engine temperature was calculated using a thermo-mechanical FE analysis.

FATIGUE BACKGROUND

The strain-life relationship for crack initiation under uniaxial stresses is

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad (1)$$

where	$\Delta\varepsilon$	is the applied strain range
	$2N_f$	is the endurance in reversals
	σ'_f	is the fatigue strength coefficient
	ε'_f	is the fatigue ductility coefficient
	b	is the fatigue strength exponent
	c	is the fatigue ductility exponent

and the values of σ'_f ε'_f b and c are obtained from constant strain-amplitude tests on smooth polished specimens subjected to uniaxial stresses.

This equation is used with a Rainflow cycle counting algorithm to identify fatigue cycles and incorporate the effects of materials memory for fluctuating stresses. For example, in Figure 2, the stress change from A to D is modelled using a stress-strain curve from point A to point D.

For biaxial stresses, McDiarmid [1972] proposed an analysis based on the plane of maximum shear stress amplitude, modified by the stress normal to the plane.

Brown and Miller reformulated this in terms of shear and normal strains, and the form of equation proposed by Kandil, Brown and Miller [1982] is widely used.

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

where $\Delta\gamma_{max}$ is the shear strain range on the plane of maximum shear strain range, and $\Delta\varepsilon_n$ is the range of normal strain on this plane.

The constants are chosen so that the equation gives the same calculated fatigue life as (1) for uniaxial stresses.

To incorporate the effects of mean stress, (2) has been extended using a variation on the Morrow mean stress correction

$$\frac{\Delta\gamma_{max}}{2} + \frac{\Delta\varepsilon_n}{2} = 1.65\,\frac{\sigma'_f - \sigma_m}{E}(2N_f)^b + 1.75\,\varepsilon'_f\,(2N_f)^c \qquad (3)$$

where σ_m is the mean stress in the cycle.

Chu and Conle have proposed that a variation on the uniaxial Smith Watson Topper mean stress correction be applied to the Kandil, Brown, Miller equation (2), giving

$$\Delta\gamma\,\tau_{max} + \frac{\Delta\varepsilon_n}{2}\,\sigma_{max} = f(2N_f) \qquad (4)$$

Again the right hand side of the equation is derived by considering the uniaxial stress case. Good agreement with test data has been reported when using this equation (see Chu [1996])

These equations were derived for in-phase principal strains. For out-of-phase loading, they have been extended using critical plane procedures. In critical plane analysis, the time history of the strains on a chosen plane is calculated. Bannantine [1989] showed that three basic planes are required for analysis using shear strains, for cracks which initiate from the surface. Each plane is rotated through 180°, and the plane with the highest calculated damage is presumed to indicate the fatigue life.

For analysis of strain gauge data, a modified two-surface kinematic hardening model (Mroz [1967]) has been proposed to calculate stresses.

For analysis of strains from elastic FEA, several proposals have been made to estimate elastic-plastic notch stresses and strains from elastic FEA stresses. For in-phase biaxial stresses, Glinka and co-workers (Moftakhar [1993]) equate the total strain energy (or strain energy density) on the two planes of non-zero principal stress. On the surface of the a model, if S_1 , S_2 , e_1 , e_2 are the in-plane principal stresses and strains from an elastic FEA, and σ_1 , σ_2 , ε_1 , ε_2 are the corresponding elastic-plastic stresses and strains, then

$$\sigma_1 \varepsilon_1, + \sigma_2 \varepsilon_2 = S_1 e_1 + S_2 e_2 \qquad (5)$$

To apply the equation, the cyclic stress-strain and hysteresis loop curves are modified for the effects of biaxial stress. The results agree well with measured elastic-plastic strains in machined grooves.

Barkey [1993], Glinka, and others have proposed methods which can be applied to out-of-phase biaxial stresses.

Software incorporating these concepts gives acceptable results for many engineering components when the mean stresses are of a similar magnitude to, or smaller than, the stress amplitudes. However, engine components can experience very high compressive mean stresses which reduce the allowable stress amplitudes (see Winship [1993] for example). Mean stress corrections based on the Morrow or Smith Watson Topper expressions are not valid for these conditions, and work is in progress to develop mean stress corrections for conditions of high compressive mean stresses.

ANALYSIS AND RESULTS

The fatigue analysis used the FE-SAFE software from Safe Technology. FE-SAFE accesses the ODB results database of ABAQUS 5.8, and writes fatigue analysis results to the ODB. The fatigue life results can then be displayed as 3-dimensional contour plots using the ABAQUS 5.8 graphics.

In this analysis, FE-SAFE superimposed the four types of loading. The centrifugal stresses were multiplied by a time history of centrifugal force based on reciprocating mass and engine speed. The gas pressure stresses were multiplied by the pressure curve. These calculated time histories of nodal stresses were superimposed on the time histories of nodal stresses from the piston-to-cylinder contact and from the thermo-mechanical analysis.

The fatigue lives at each node were calculated. FE-SAFE also calculates fatigue strength factors at each node for a specified design life. The analysis included the effects of temperature on the fatigue properties of the material. Materials test data for three temperatures was entered into the database. At each node FE-SAFE reads the nodal temperature, and calculates fatigue endurance data specific to the temperature at the node.

The contour plot of fatigue lives is shown in Figure 3. The analysis has identified the most critical fatigue crack initiation sites, and these agree well with test results. The calculated fatigue lives are also consistent with test data.

FUTURE WORK

Work is continuing on algorithms to calculate elastic-plastic stresses from the elastic FEA, for the general case of out-of-phase stresses with fluctuation stress amplitudes. Further work on the effects of large compressive stresses is also proceeding.

REFERENCES

Bannantine J A, 1989

A variable amplitude multiaxial fatigue life prediction method

PhD Thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois

Barkey M E, 1993

Calculation of notch strains under multiaxial nominal loading.

PhD Thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois

Chu C, Conle F A, Hubner A, 1996

An integrated uniaxial and multiaxial fatigue life prediction method

VDI Berichte NR 1283

Kandil F A, Brown M W, Miller K J, 1982

Biaxial low cycle fatigue fracture of 316 stainless steel at elevated temperatures

Book 280, The Metals Society, London

McDiarmid, D L, 1972

Failure criteria and cumulative damage in fatigue under multiaxial stress conditions. PhD Thesis, City University, London

Moftakhar A, Buczynski A, Glinka G, 1993

Calculation of elasto-plastic strains and stresses in notches under multiaxial loading.

Mroz Z, 1967

On the description of anisotropic work-hardening.

Journal of the Mechanics and Physics of Solids 15:163-175.

Winship M, Morgan W J, 1993

Piston Design for the Nineties

SAE Paper 930273, in New Diesel Engine and Components (SP-961)

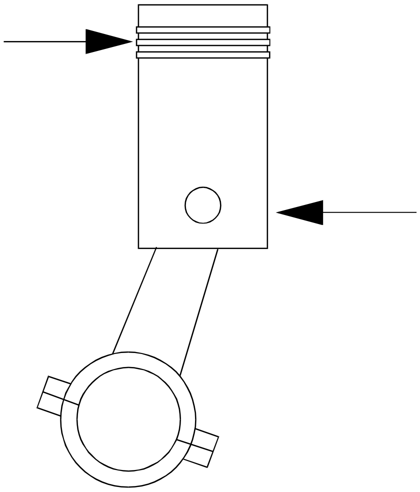

Figure 1 Piston-to-cylinder contact.

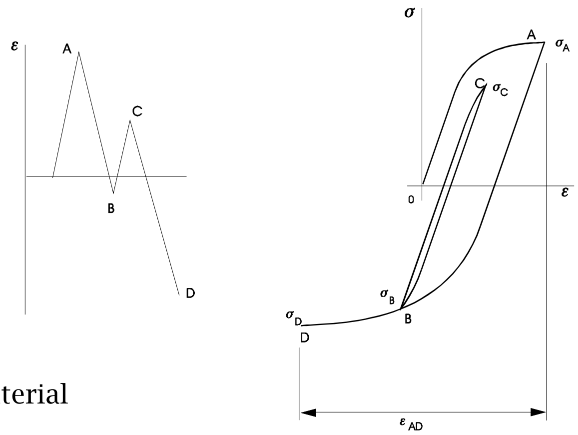

FIGURE 2 Effect of material memory.

Figure 3. Fatigue life contours for the piston.