Low Cycle Fatigue Simulation of Valve Bridge Region in Cylinder Head Based on Critical Plane Model

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Abstract

The reason of this study is low cycle failure of cast iron cylinder head during the E5 standard durability test. The goal of the present investigation is durability test simulation and low cycle fatigue life evaluation of cast iron cylinder head. With uncouple structural analysis, preloads, thermal and mechanical load and boundary conditions are prescribed to finite element model of the cylinder head. To cover the durability test, the analysis steps repeated at five crack speed, 750, 1650, 2075, 2350 and 2600 rpm. The cylinder head is subjected to cyclic multi-axial non-proportional variable amplitude loads. In fatigue analysis, critical plane model with cumulative damage theory is applied to predict fatigue life. A general scripting is developed and validated to calculate fatigue life. The results show that the failure of critical cylinder head is the type of low cycle fatigue. The valve bridge region, where high temperature exists during operation of the engine, is the critical area in cast iron cylinder head in fatigue analysis approach. The simulation results are in accordance with the results of durability test.

***Keywords**: cylinder head, cast iron, fatigue*

1. Introduction

Due to the increasing demand for higher specific engine power and better overall efficiency some engine components require special attention during the development process as they have to be designed much closer to their mechanical limits. One of these components is the cylinder head, which thereby becomes more and more critical in terms of thermo-mechanical fatigue behavior.

The cylinder head is one of the most complex parts in the engine, and it endures high thermal and mechanical load during working cycles [1]. The nose bridge on the head between the inlet valve and exhaust valve is subjected to the hot air through the exhaust valve and the cool air through the inlet valve simultaneously, and it is the weakest part in the cylinder head. The fatigue in the nose zone is one of the most important factors that shorten the life of a cylinder head [1].

Shalev and et al [2] an experimental and theoretical study carried out to investigate the mechanism of crack development in cylinder heads of two stroke diesel engine. They showed that crack initiate in the valve bridge region, between a pair of exhaust valve, where high temperature exist during operation of the engine. Beck and et al [2] investigated on Thermal-mechanical fatigue behavior of cast aluminum alloys for cylinder heads. Wang and Yao [3] evaluated several multi-axial fatigue criteria. Rahman and et al [4] presented the assessment of multi-axial fatigue criteria for the cylinder head of new two-stroke free piston linear engine using the finite element analysis technique. They investigated on prediction of fatigue life and effect of the stress combination for the proportional loading condition. They showed that the biaxiality correction method give the conservative predicted results as compared to the uniaxial loading. They also showed that the materials parameter correction method gives the most conservative prediction with the SWT criteria. Mendes and Cardoso [5] presented the methodology for structural analysis of a high-speed Diesel engine aluminum cylinder head for Pick-up application, considering the finite element method. Minichmayr [6] experimentally evaluated different lifetime approaches to fulfill the requirements for the fatigue analysis of engine components made of aluminum.

Besides damage parameters and energy criteria, the complex damage rate model of Neu/Sehitoglu was evaluated. Approximately 20 parameters determined to take into account damage due to mechanical fatigue, oxidation and creep. Trampert and et al [7] presented a feasible procedure to set up material models and estimate service life of cast iron cylinder heads under variable thermo-mechanical loading conditions by the use of computer-aided engineering tools. They showed the influence of thermal load and mechanical constraints on thermal-fatigue model life span. Tsuyoshi-Takahashi and Sasaki [8] focused on Low cycle thermal fatigue of aluminum alloy cylinder head in consideration of changing metrology microstructure. Grieb and et al [9] studied several cast aluminum alloys with respect to their thermal and mechanical properties. In addition to standardized specimens, they tested near component-shaped samples under thermo-mechanical fatigue conditions in a testing device which represents near-service conditions, in order to characterize life until a long crack was formed. The sample geometry tried to represent the valve bridge of a diesel cylinder head, which was known to be the most thermo-mechanically loaded and hence critical part in this component. Mottas and et al [10] studied the fatigue properties and micro-mechanism of fracture of a cast alloy used in diesel Engine cylinder head. Augustins [11] developed an empirical criterion, based on the modification of one parameter of the Dang Van criterion with respect to the biaxiality rate and to the load ratio. The criterion was successfully tested on an important number of biaxial fatigue tests from the literature and on cylinder head simulations.

While the deformation and damage behavior of aluminum cylinder heads under complex thermal mechanical loading has been the subject of numerous studies in the past, cast iron cylinder heads have been in the focus of thermo-mechanical fatigue only to a minor extent [7].

The reason of this study is low cycle failure of cast iron cylinder head during the E5 standard durability test. The goal of the present investigation is durability test simulation and low cycle fatigue life evaluation of the cast iron cylinder head. Because of multi-axial non-proportional variable thermo-mechanical load is subjected to cylinder head, a general script is developed to use as a post-process of stress analysis based on fatigue model.

2. General Scripting

2.1 Algorithm

There are some fatigue prediction software's that are limited to several classic fatigue models. The investigations show that any fatigue model is limited to some materials or loads. For example, the maximum normal stress fatigue model is applicable in problems under proportional loading but it's not applicable in those under non-proportional loading. Therefore writing the general code to calculate fatigue life distribution in deformed body based on new developed models could be helpful for designer.

In this study, a general scripting is developed to calculate fatigue life in deformed body based on critical plane criteria. The scripting is written in python language that is completely compatible with FEM analysis ABAQUS software. The inputs of the general script are the stress and strain field in deformed body and fatigue properties of it. The output of the general script is the scalar field of fatigue life prediction in graphical format. The life prediction based on the user opinion is done using one of the critical plane criterions. Mathematical formulation is based on tensor calculus. The algorithm of program present in Fig. 1 as following:

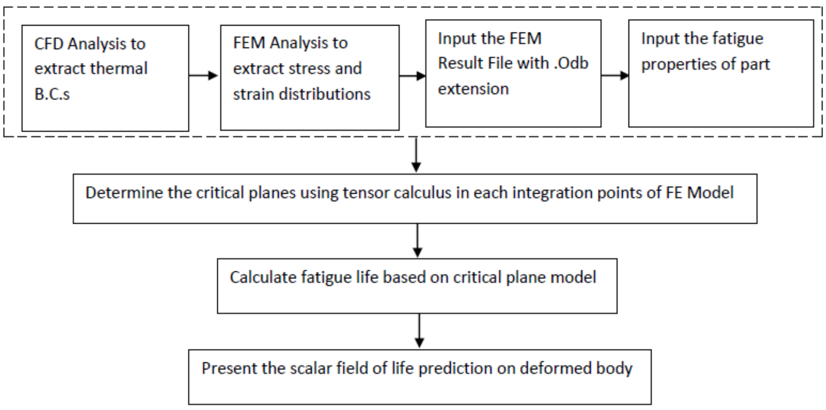

Fig1. The algorithm of fatigue life prediction based on FEM results and Critical Plane models.

2.2. Validation

To evaluate the results accuracy of developed fatigue life prediction script, a comparison is made of between estimated life with proposed program and those obtained in literature.

A sheet with central circular hole subjected to cyclic uniform tension is the benchmark problem to evaluate multi-axial fatigue models. The concentrations and the gradients of stress and strain cause the multi-axial stress distribution near the hole. Cowell [12] developed a practical fatigue analysis methodology for life prediction of rotary-wing aircraft components. He studied on the AISI 4340 sheets. During the investigations, he presented the experimental and numerical fatigue life of a sheet with central circular. The uniform tension is applied so that the stress ratio, R, is zero and the maximum principal stress is variable between 50 to 80 ksi in several tests. The strength and fatigue properties of AISI 4340 sheets are presented in Table 1.

Table 1: The strength and fatigue properties of AISI 4340 [12]

Properties	*Magnitudes*
Ultimate tensile strength (σ_u)	*212 ksi*
Endurance limit (σ_e)	*55.83 ksi*
Fatigue strength coefficient (σ'_f)	*290 ksi*
Fatigue strength exponent (b)	*-0.091*
Fatigue ductility coefficient (ε'_f)	*0.48*
Fatigue ductility exponent (c)	*-0.60*
Strain hardening coefficient (K)	*305 ksi*
Strain hardening exponent (n)	*0.15*
Modulus of elasticity (E)	*30000 ksi*
Poisson's ratio (ν)	*0.3*

Table 2: The comparison of fatigue life prediction obtained with [12] and present study

Max. Tensile Stress (ksi)	Present Study	Experiment [12]	Numerical [12]
50	*4.17e6*	*1.82e6*	*0.29e6*
60	*4.00e5*	*3.31e5*	*0.72e5*
70	*4.68e4*	*9.51e4*	*2.6e4*
80	*1.15e4*	*3.7e4*	*1.2e4*

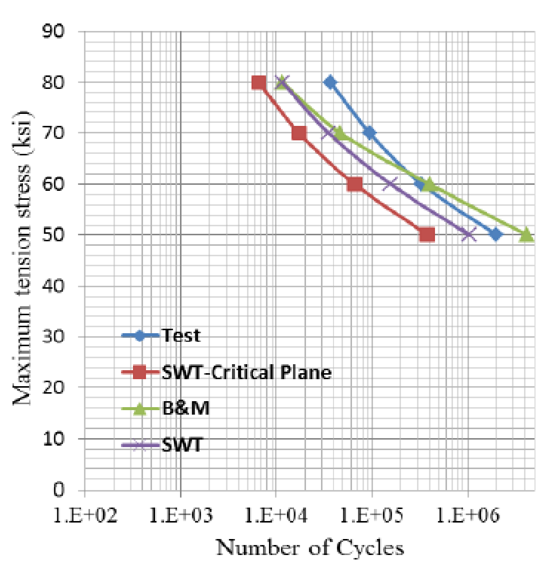

Fig2. The comparison of experimentally fatigue life prediction obtained with [12] and present study

The experimental and numerical fatigue life prediction of the sheet obtained with [12] and those obtained with this study are compared in Table 2. The numerical fatigue life predictions with [12] and present study is calculated based on Brown & Miller model. The differences between present study and experimental results are acceptable in fatigue analysis approaches. Generally, the estimated life with present study is closer to experimental results [12], in comparison with numerical result with [12]. In Fig. 3 the experimental results obtained with [12] are compared with numerical results obtained in this study using SWT, SWT-critical plane and Brown & Miller models. The results show that the Brown & Miller model is the best criterion among above models to predict fatigue life in this problem.

3. Cast iron Cylinder Head

In this section, the strength and fatigue life of cast iron cylinder head is studied. According to the standard, the analyses in five crank-speed, 750, 1650, 2075, 2350 and 2600 rpm are performed. Analyses including three steps to simulation of cylinder head durability as follow:

First step: fluid analyses to extract the required boundary conditions in next step

Second step: stress analysis to extract the stress and strain fields in cylinder head

Third step: fatigue analysis based on stress and strain fields, critical plane theory and cumulative damage theory.

In following subsections, the first and second steps are briefly addressed, and then fatigue analysis of cylinder head is presented.

3.1 Fluid analysis

The cylinder head is subjected to thermal load of coolant, thermal and mechanical load of combustion gas and mechanical preloads of bolts and seat tolerances. Decouple assumption is used to structural analysis. It means that the thermal load of coolant on water jackets is extracted based on three dimensional CFD analyses, and then the calculated thermal load is prescribed on cylinder head in stress analysis step.

3.2. Structural Analysis

The following decouple procedure is used to apply mechanical and thermal loads on critical cylinder head at five crack-speeds:

I. Bolt load
II. The load due to tolerance in seats
III. Combustion gas pressure
IV. Thermal load due to coolant and combustion gas

To brief the letter, the results stress distributions in critical cylinder head are only presented at crank-speed 2600 rpm. The surface zones between valves endure the maximum thermal load. According to literatures, this region is a first candidate to nucleate surface cracks. Because of the cylinder is subjected to multi-axial stress, the critical zone is determined using equivalent stress field. In Fig. 8 the minimum principal stress, which is known as a compression stress, in critical cylinder head is shown.

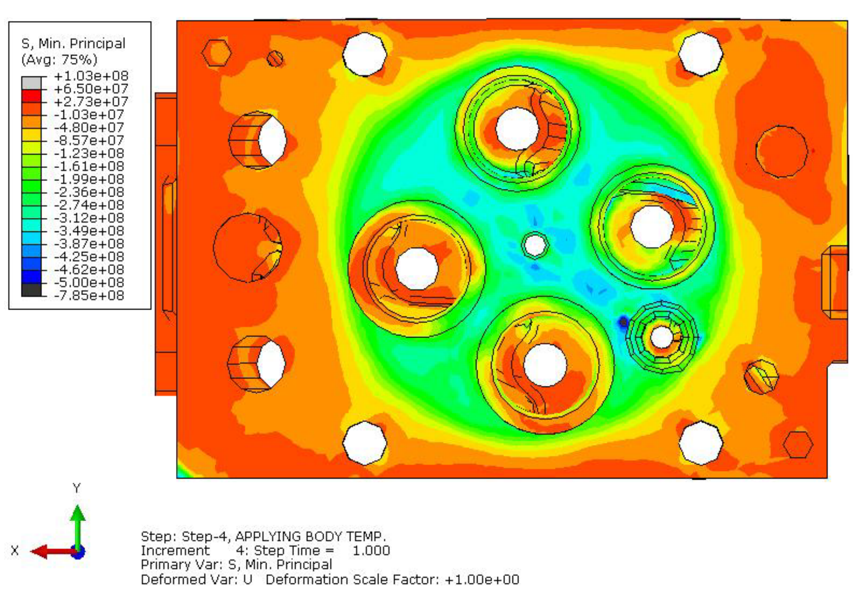

Fig3. Stress distributions in critical cylinder head at crank-speed 2600 rpm

3.3. Fatigue life prediction

The cylinder head is one of the most complicated parts to fatigue life analysis. This is because that it is subjected to multi-axial non-proportional variable amplitude thermo-mechanical loads. In addition, the complicated geometry increases the difficulties in pre-processing and processing steps.

The classical fatigue models could not predict correct fatigue life in such problems. Therefore a critical plane model defined as a بsochie-Fatemi Modelپ[13] is used to estimate the fatigue life. In Fig. 8 the scalar field of logarithmic predicted number of cycles for cast iron cylinder head is presented at crank-speed 2600 rpm. To evaluate the area of critical zone that endures the limited fatigue life, the predicted number of cycles is presented in Fig. 9. To clarify, the unlimited life zones are shown in gray color. It is considered that the valve bridge regions, where high temperature exists during operation of the engine, experience the limited life, about one million cycles. In order to improve the fatigue life, it should be prescribed some changes to decrease the stress and the strain in cylinder head during operation of the diesel engine. Because of complexity in engine parts design and dependency of them to others, geometry modification is not reasonable and economic solution..

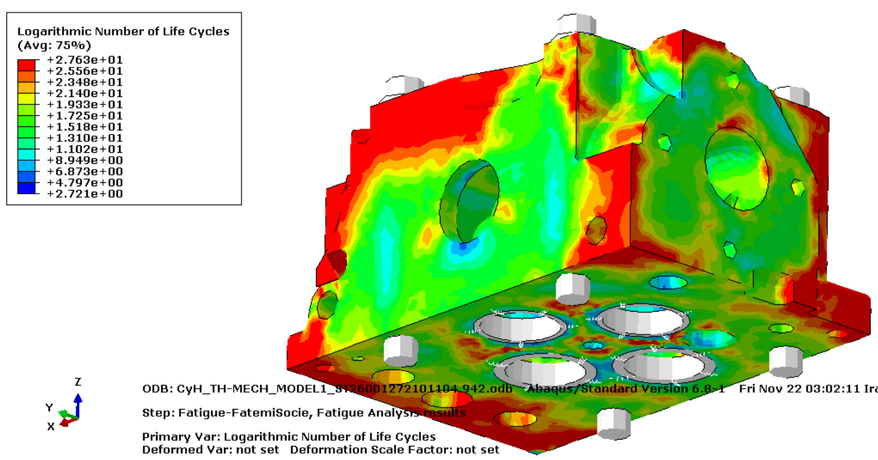

Fig4. The scalar field (logarithmic number of cycle) of predicted life at 2600 rpm

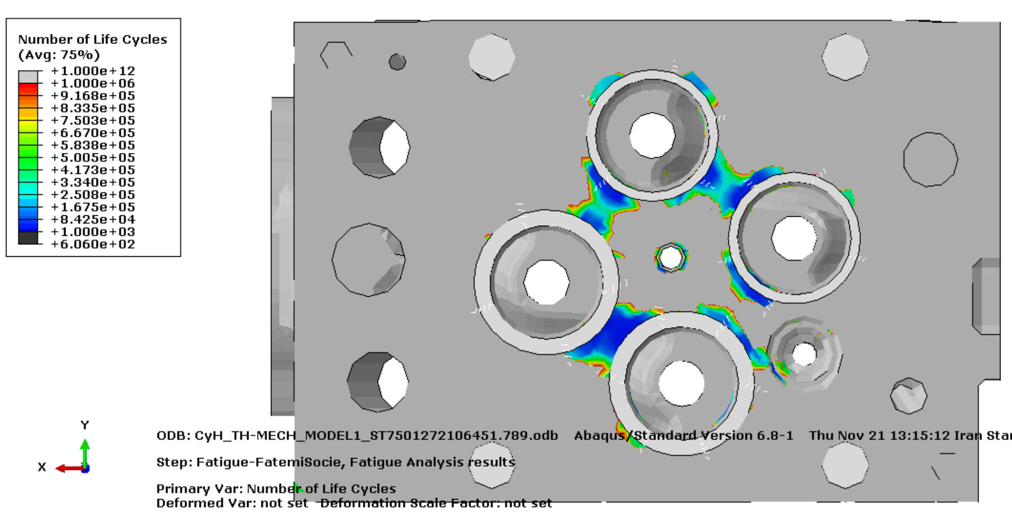

Fig5. The scalar field (number of cycle) of predicted life at 2600 rpm

Another choice is creating compression residual stress with shot peening or rolling at critical area, To cover the E5 durability test, simulations are repeated at other crank-speeds and the fatigue life of the cylinder head during the test is predicted using cumulative damage theory. The results show that the failure of critical cylinder head is the type of low cycle fatigue. It means that the number of E5 test cycles before failure of cylinder is about 1000 cycles. This is because that the above region experiences the combination of high thermal and mechanical loads that results high thermo-mechanical multi-axial strain and biaxial stress in surfaces. In this condition the micro cracks grows and after several cycles, the cracks become semi-elliptical in shape. By continuing the cyclic loading, semi-elliptical cracks grow and meet, leading to cylinder failure. As considered in Fig. 9 the nucleation of surface cracks will be happen in valve bridge regions as a low cycle fatigue type. The recent results are in accordance with experimental results of the cast iron cylinder head durability test. Hence, the prepared sequence simulations can predict the strength and fatigue life of the modified cylinder head in next studies of authors

Conclusions

In this study, the low cycle fatigue life of cast iron cylinder head in six stroke engine is investigated. The goal of the investigation is E5 durability test simulation and low cycle fatigue life evaluation of cast iron cylinder head. This is because the failure of cylinder head during the experiment as a low cycle fatigue type. Because of cast iron cylinder head is subjected to multi-axial non-proportional variable amplitude loads, the classical fatigue models could not predict correct fatigue life. A general script was developed and validated to calculate fatigue life of a FEM model based on critical plane theories. All of analyses were repeated at five crank-speeds of E5 cycle test including 750, 1650, 2075, 2350 and 2600 rpm. Cumulative damage theory is used to estimate the life cycle in durability test. The results show that the failure of critical cylinder head is low cycle fatigue type. The valve bridge region was known as a critical area in cast iron cylinder head in fatigue analysis approach. The simulation results are in accordance with the results of durability test.

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