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FEA BASED DURABILITY USING STRAIN-LIFE MODELS FOR DIFFERENT MEDIUM CARBON STEEL AS FABRICATION MATERIALS FOR AN AUTOMOTIVE COMPONENT

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ABSTRACT

There has been a strong trend towards the adoption of optimum materials and components in automotive industry. Automotive designers have a wide range of materials and processes to select from. Fatigue assessment of SAE1541_362_QT and SAE1045_390_QT steels for automotive component particularly for a lower suspension arm, have been numerically studied using finite element analysis under random loading conditions. Both Morrow and Smith-Watson-Topper (SWT) strain-life models have been used for live estimation. These two models were often been used in the fatigue life assessment for metallic components. The results of this paper are based on analytical investigations, including detailed finite element strain analysis as well as fatigue and optimisation studies. Comparison of predicted lives indicates that the SWT-based estimation analysis method gave longer life than the Morrow estimation. In addition, steel for fabricate the lower suspension arm gave higher durability compared to SAE1541_362_QT steel. Such results provide further credit to the appropriately of using SWT as a prediction model, as well as, SAE1045_390_QT steel as a fabrication material of the automobile lower suspension arm.

***Keywords*:** Fatigue life assessment; **F**inite element; medium carbon steel; Lower suspension arm; Variable amplitude loading.

INTRODUCTION

Engineers have recognized for over 150 years that metals can fail in fatigue. Modern fatigue analysis came to life in the 1980s when in-vehicle load measurement became available with analysis software and low-cost computers. In automotive design, durability evaluation of components based on experimental assessments is time-consuming and expensive, so analytical approaches that include limited number of component verification tests have gained more attention (Kim et al., 2003). The analytical approach combined with a limited number of component testing reduces design cycle time due to reduced testing, allows inexpensive evaluation of changes in geometry, material, loading and manufacturing process through performance simulation, and finally provides evaluation techniques for product optimization and failure analysis (Ali and Mehrdad, 2002). The finite element method (FEM) has become a powerful tool for the numerical solution of a wide range of engineering problems (Clough, 1960). Results are important in calculating and verifying safe part lifetimes. In the past, durability analysis was largely the province of research. In classic structural analyses, failure predictions are solely based on the material strength or the yield strength.

Carbon can be considered as the only alloy element in Plain carbon steel. Carbon being a powerful alloying agent can give a variety of strength and hardness by varying its composition in the steel. It is in this regard that carbon steel can be classified as low, medium and high carbon steel. Lindberg (1977) discussed about the carbon steel with carbon content between 0.3 and 0.6% is termed medium carbon steel. While those with lower and higher are respectively classified as mild and high carbon steel. In a study by Devlukia and Bargmann (1997) conducted the fatigue assessment of a suspension arm using the deterministic and probabilistic approaches. The strength reduction effect due to the surface roughness was accounted for by representing the surface as a collection of notches and making use of Neuber’s rule. It was concluded that the residual stress demonstrated a more pronounced effect under constant amplitude loading as compared to variable amplitude loading. The cumulative damage potential under the variable amplitude loading sequences of the long duration on a simple specimen data and strain-life method was conservative by a factor of two.

A work from Haiba *et al*. (2002) has been seen as a finite element analysis (FEA) application in fatigue life estimation. They estimated the fatigue lives of metallic material in both time and frequency domain methods under FEA. Comparison between several approaches to fatigue life prediction using a real automotive engineering case study has also been performed. In addition, the study was taking into account the optimisation based on fatigue life which requires accurate relative distribution rather than exact values.

Another work by Haiba *et al.* (2003) introduced a new structural optimization algorithm based on fatigue life. The paper investigates the effects of different assessment strategies on the predicted fatigue life of a lower suspension arm, the properties of which are modified to generate different degrees of interaction between the arm natural frequencies and the frequency range of the applied forcing functions. The results of this investigation were used to derive a new form of structural optimization algorithm which is more robust and efficient.

In different situation, Kim *et al.* (2003) analyzed the hydroforming process of an automobile lower arm using finite element program of HydroFORM-3D in order to accomplish its proper design and the process control. This work showed that the FEM program of HydroFORM-3D provided valuable information regarding to the forming process and was also dramatically improved the potential of the hydroforming process. Though the computer-aided design approach was proposed in this study, the designer can improve the design efficiency, as well as to avoid expensive and time-consuming trial-and-error and extensive process design experience.

Then Fatemi and Zoroufi (2004) did an experimental and analytical work using FEA, the durability assessment and also an optimization analysis. They developed methodologies that can be applied to a wide range of automotive and other components. Some of the findings are the FEA simulation for cyclic loadings which is important for fatigue damage analysis. The life prediction based on local approaches, i.e. the Morrow's mean stress parameter provided better predicted fatigue lives than the Smith-Watson-Topper's (SWT) mean stress parameter.

In a case study by Xianjie (2005), he investigated the cyclic strain low cycle fatigue and cyclic stress ratcheting failure of carbon steel 45 with quenched and tempered treatment. The tests for this cyclic strain low cycle fatigue with or without mean strains were carried out in order to investigate the effect of the mean strain on low cycle fatigue behavior. The evaluation equation of fatigue damage was then proposed based on the symmetric cyclic strain LCF testing results, and the equation was used to evaluate the effect of the fatigue damage on the ratcheting failure under different cyclic stressing.

In a work by Zoroufi and Fatemi (2006), the fatigue behavior of vehicle suspension components (forged steel and cast aluminium steering knuckles) were investigated under constant-amplitude load-controlled fatigue tests. Three of the finite element models of the knuckles were analysed using linear and non-linear methods. The nominal stress, the local stress, and the local strain life prediction approaches were then employed and compared to the experimental results in order to evaluate the accuracy and validity of these approaches. It was observed that among the contemporary life prediction procedures used in the automotive industry, the local strain approach using linear elastic FEA results in conjunction with Neuber-corrected stresses were reasonable. In addition, it has been found that the results were close to those obtained on the basis of non-linear elastic-plastic FEA.

The aim of this paper is to examine the effect of two medium carbon steel materials on the durability of an automotive lower suspension arm using finite element analysis. It has been obtained that SAE1045_390_QTsteel has the priority to consider as the fabrication material for the automotive lower suspension arm.

LITERATURE BACKGROUND

The strain-life method was applied for estimating the fatigue life of the lower suspension arm because for suspensions parts it is important to predict crack initiation in order to avoid fatigue failure by removing the part from service at the appropriate time. In the same time, most of the time to failure consists of crack initiation (Dowling, 1999), thus, a conservative approach is to denote the component as failed when a crack has initiated. The fatigue life is performed using the strain-life approach, Morrow (1968) and Smith *et al.,* (1970) for two kinds of medium carbon steel which have been chosen as a fabricated materials for the lower suspension arm because their ability to used as forging automotive components.

Fatigue life prediction represents one of the application for FE. Among the plastic strain models, the Coffin-Manson, Morrow, SWT are widely used. Each of these models is an empirical relationship between cycles-to-failure, and analytically, numerically or experimentally determined plastic strain range per cycle. The three models are described in the followings:

The first strain-life model is the Coffin-Manson relationship (Lindberg, 1977),

$$\varepsilon_a = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \quad (1)$$

where E is the material modulus of elasticity, ε_a is a true strain amplitude, $2N_f$ is the number of reversals to failure, σ'_f is a fatigue strength coefficient, b is a fatigue strength exponent, ε'_f is a fatigue ductility coefficient and c is a fatigue ductility exponent.

Based on the proposal by Morrow [12], the relation of the total strain amplitude (ε_a) and the fatigue life in reversals to failure ($2N_f$) can be expressed as

$$\varepsilon_a = \frac{\sigma'_f}{E}\left(1 - \frac{\sigma_m}{\sigma'_f}\right)\left(2N_f\right)^b + \varepsilon'_f \left(2N_f\right)^c \qquad (2)$$

where σ_m is the mean stress. Another strain-life mean stress correction model was suggested by Smith *et al.* (1970)**,** or often called the SWT parameter. This relationship was based on strain-life test data which was obtained at various mean stresses. Thus, the SWT expression is mathematically defined as

$$\sigma_{max}\, \varepsilon_a E = \left(\sigma'_f\right)^2 \left(2N_f\right)^{2b} + \sigma'_f\, \varepsilon'_f\, E\left(2N_f\right)^{b+c} \qquad (3)$$

where σ_{max} is the maximum tensile stress for the particular cycle. This equation is based on the assumption that for different combinations of strain amplitude, ε_a , and mean stress, σ_{max} , the product $\sigma_{max}\ \varepsilon_a$ remains constant for a given life.

METHODOLOGY

1- Material Specification

In order to classify the lower suspension arm material specification, analyzing the chemical composition of the steel sample is done. Based on table 1, the steel can be classified as medium carbon steel , since both AISI and SAE classified steel whose carbon content ranges between 0.3-0.6%, manganese content ranges between 0.60-0.9% to be medium carbon steel (Lindberg, 19770) which represents the fabricated material for the 2000 cc Sedan lower suspension arm . The measured values have been get using INCA Energy system. Three samples were cut from the lower suspension arm using a cutter. The samples were subsequently ground with successive SiC papers (grit 200-1200) and then polished with polishing cloth and Alomina solution of grain size 6µm then 1µm.

Table 1: Chemical composition of the steel

Element	C	Mg	Si	V	Cr	Ni	Mn	Fe
Measured wt%	0.3	0.13	0.	0.04	0.14	0.49	0.9	Bal.

2- Finite element analysis

2-1 Geometrical and finite element model

A geometric model of a lower suspension arm for a 2 Liter engine Sedan car is considered in this study, and this component is presented in Figure 1. The finite element approach is used for modeling and simulating. Three-dimensional lower suspension arm model geometry is drawn using CATIA software, as shown in Figure 2.

Fig. 1: A geometric model of a lower suspension arm

The auto tetrahedral meshing approach is a highly automated technique for meshing solid regions of the geometry. It crates a mesh of tetrahedral elements for any closed solid including boundary representation solid. Tetrahedral meshing produces high quality meshing for boundary representation solids model imported from the most CAD systems. The TET10 mesh can give more accurate solution since the 10 nodes tetrahedral (TET10) element is used for the analysis with the adoption of a quadratic order interpolation function. There are three main parts in the lower suspension arm which their behaviour has been considered in the FE boundary conditions, ball joint, pivot 1 and pivot 2. The FEM (Figure 2) has boundary conditions as followed

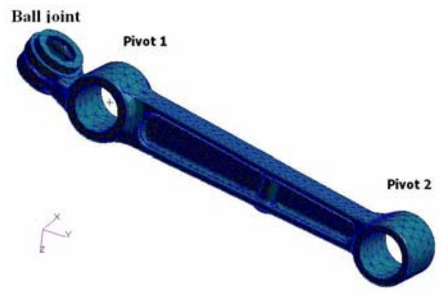


Fig. 2. Finite element model of the lower suspension arm

distributed load has been applied on the inner surface of pivot 1. Pivot 2 considers as a rigid section with a rotation around *x*-axis from the side of the vehicle body. In the same time, rigid has been considered on the ball joint with translations in *x* and *y* direction while rotation around *x*, *y*, and *z*-axis to represent the braking and cornering loads. There are no acceleration loads as inputs, due to collecting data during driving of the car at constant velocity.

2-2 Loading information

The load history which has been used for this analysis was obtained from the real automotive lower suspension arm, which was driven over country road. The frequency sampling, f_s for this case is 500 Hz. This f_s value was chosen in order to collect a wide range of road data (Oh, 2001; Stephens *et al.*, 1997). The data was measured using a fatigue data acquisition system

(Figure 3) at car velocity of 25 km/h, and, recorded data in a form of strain time histories.

Fig. 3: The setup of fatigue data acquisition system data collection.

A strain gauge was fixed in an exact position on the lower suspension arm as shown in figure 4. Finite element analysis was performed in order to classify the critical areas in order to get clear idea to choose the positions area for fixing strain gauge during the experimental test to get the strain history data, as shown in Figure 5.

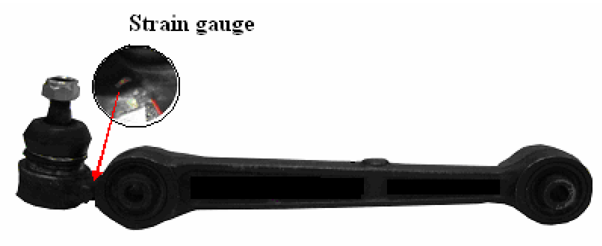


Fig. 4: Strain gauge location on the lower suspension arm

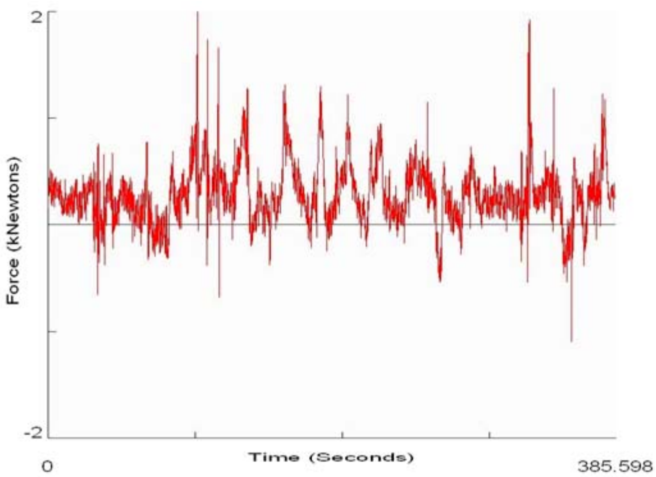


Fig. 5: Experimental loading history for the lower suspension arm.

RESULTS AND DISCUSSION

Fatigue life assessment for the lower suspension arm was carried out using CATIA software for model generation, MSC Patran for pre-processing, MSC Nastran for the strain analysis and MSC Fatigue for the fatigue analysis. Linear finite element model of the lower suspension arm was analysed. In fact, the local strain, or crack initiation approach to fatigue life estimation requires accurate values of local elastic-plastic stresses and strains, especially at free surfaces. In principal, these can be obtained through non-linear FEA, but this approach is usually impractical for lengthy and complex load histories. For this reason elastic-plastic stresses and strains are commonly estimated using a combination of linear elastic FEA and a notch correction procedure (elastic-plastic correction) (Heyes *et al.,* 1995). The finite element analysis (FEA) has been performed using SAE1541_362_QT steel and SAE1045_390_QT steel as these steels used for fabricate the automobile lower suspension arm. The strain value from the analytical simulation was within the range of the collected data during driving of the car on the road. This was due to accurate boundary conditions and static load in the pre-processing stage. For the fatigue analysis stage and after applying the road data as fatigue load, the fatigue life results are obtained as shown in table 2. It shows the fatigue component life results using Morrow and SWT strain-life methods for the two medium carbon steels, coded SAE1541_362_QT and SAE1045_390_QT. The fatigue life contour for this case is shown in figure 6. For the purpose of this FEA simulation, the polished surface finish has been used.

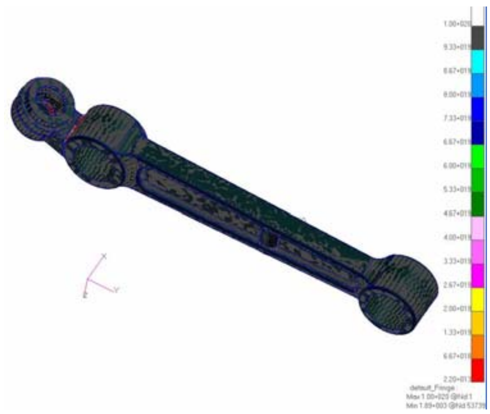


Fig. 6: Model fatigue life contour

From the Morrow model results of table 2, longer life can be obtained for the steel type of SAE1541_362_QT compared to SAE1045_390_QT while the opposite results can be obtained when used SWT strain life model. It is difficult to categorically select one procedure in preference to the other. However, for loading sequences which are predominantly tensile in nature the Smith Watson Topper approach is more conservative and is, therefore, recommended. In the case where the loading is predominantly compressive, particularly for wholly compressive cycles, the Morrow correction can be used to provide more realistic life estimates.

Table 2: Fatigue component life using Morrow and SWT for SAE1541 and SAE1045_390_QT steel

Material	Fatigue life (Cycles)	
	Morrow	SWT
SAE1541_362_QT	8706	9530
SAE1045_390_QT	8317	10606

The behaviour study of these two material type is shown in figure 7. showing that these two materials behave under cyclic loading conditions. It also shows on how their behaviour with respect to one another. SAE1045_390_QT is obviously higher strength steel with its yield point well above that of SAE1541_362_QT.

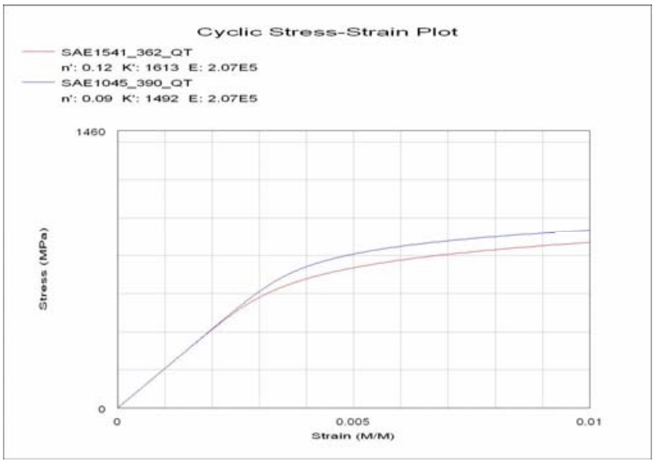


Fig. 7: Cyclic stress-strain curves for SAE1541_362_QT and SAE1045_390_QT steel

Figure 8 shows Morrow life plot for SAE1541_362_QT and SAE1045_390_QT steel which can be fully characterized by knowing four material parameters as shown in the equation 2 of the strain-life plot. In the same time, the transition point defines the difference between high cycle fatigue which represented by the right side because elastic events dominate plastic events and low cycle fatigue which represented by the left side because plastic events dominate elastic events.

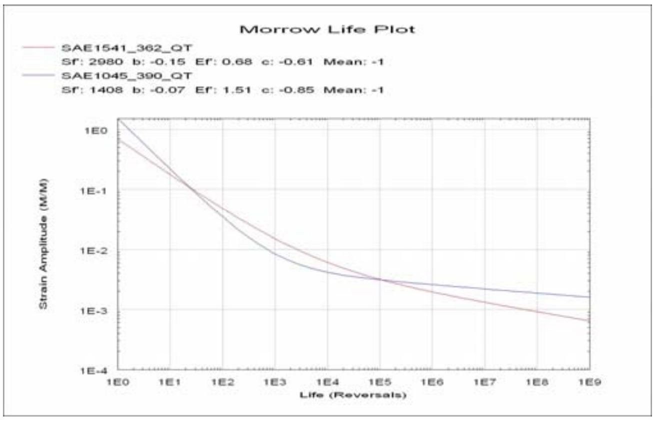
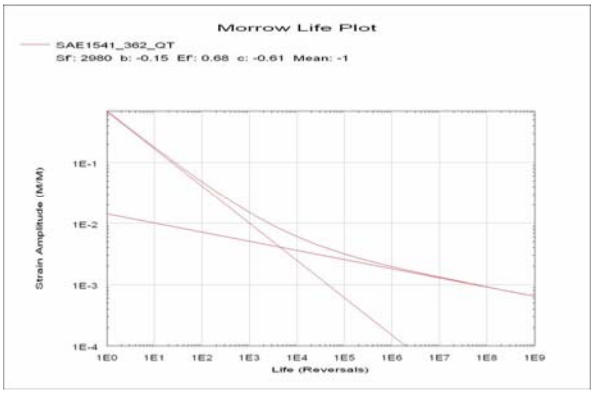
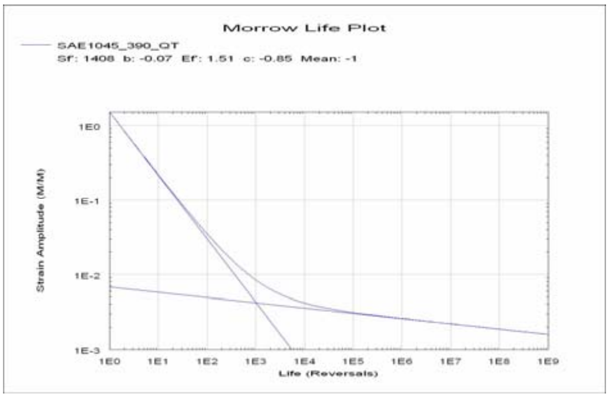


Fig. 9. Morrow life plot for medium carbon steel SAE1541_362_QT and SAE1045_390_QT

Figure 9 shows the number of cycles to failure under real road loading for SAE1541_362_QT and SAE1045_390_QT steel. A comparative for these two strain life curves can be performed. They cross each other and therefore exhibit different life behavior depending on the strain level. So it is impossible to know from the plot which would perform better in order to consider one of them as a fabrication material for the lower suspension arm, especially higher durability is the goal which is looking for.



(a)



(b)

Fig. 8. Morrow life plot for (a) SAE1541_362_QT (b) SAE1045_390_QT steel

CONCLUSIONS

FEA has been used in durability comparison of the lower suspension arm using two kinds of medium carbon steel. Fatigue life component using Morrow model gave higher durability for SAE1541_362_QT steel while SWT gave higher durability for SAE145 steel. The SWT model can be considered as the fatigue life prediction model for the case study, especially, the road loading sequence are predominantly tensile. In addition, SAE1045_390_QT shows better behavior than SAE1541_362_QT under cyclic loading which will give the priority for SAE1045_390_QT to be the fabrication material for the automotive lower suspension arm due to its high durability.

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