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A Review on Fatigue Analysis of Composite Steering Column

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Abstract

Fatigue analysis was performed in order to prevent fatigue failures and estimate the fatigue life of an automotive steering column, which is very critical for vehicle safety. Fatigue is the primary cause of failure of steering column under cyclic stresses. The cyclic loading conditions and stress concentration in the steering column are unavoidable due to its turning application and can result in fatigue failure. Due to repeated twisting, the repetitive cyclic loads are generated and cracks form on steering column. By fatigue testing we can have a better material to be selected and used for steering column in different automobile industries. Parameters which influence the fatigue life of component are important to be analyzed. Material replacement has a great influence on fatigue. Study of various properties of the composites is important in order to replace them in place of conventional materials to improve the efficiency of components.

The different specimens can be used which are taken from column tube. These are used for the monotonic tensile test and fatigue tests, which resulted in monotonic and cyclic properties of the steering column material. Local stress and strain distributions in the column are analyzed by Finite element analysis method. Experimental Strains formed at the critical locations are measured by physical methods like strain gauges. The results are used to verify the finite element analysis results.

Keywords: *Fatigue, cyclic loading, FEA, Steering column*

1. Introduction

Our familiarity with fatigue failure is so closely linked with the behaviour of isotropic, homogeneous, metallic materials that we have tended to treat modern fibre composites as though they were metals. The test methods used to study fatigue in metals have also been applied to composites, and the interpretation of the results of such tests has often been clouded by our perception of what constitutes metallic fatigue failure. It is natural that a designer wanting to substitute a composite for a metal component should want to test the new material by applying a cyclic loading régime of the same kind as the component would be required to sustain in service in order to prove that the composite will perform as well as the metal. But it must not be assumed, a priori, that there is some universal mechanism by which fluctuating loads will inevitably result in failure at stresses below the normal monotonic failure stress of the material.

Fatigue of metals accounts for a high proportion of engineering failures and has been intensively studied for more than a century. Design data have been accumulated for every conceivable engineering metal and alloy, and the engineer has access to a comprehensive set of rules, some empirical and some based on scientific understanding, with which to cope with any given design requirement, although some designers often choose to ignore these rules. Fatigue in metals progresses by the initiation of a single crack and its intermittent propagation until catastrophic failure. This occurs with little warning and little sign of gross distortion, even in highly ductile metals, except at the final tensile region of fracture. In ordinary high-cycle (low-stress) fatigue, where stress levels away from the crack tip are low, the properties of the metal remote from the crack are only slightly changed during fatigue. It is not a general feature of fatigue in metals and plastics that the strength of the material is reduced by cyclic loading, although work-hardening or work-softening may occur in metals undergoing low-cycle (high-stress) fatigue. The usual effect of fatigue at low stresses is simply to harden the metal slightly. Generally speaking, a stronger material will have a higher fatigue resistance, the fatigue ratio (fatigue limit divided by tensile strength) being roughly constant.

It is not uncommon for users of composite materials, even in the aerospace industry, to express the belief that composite materials — specifically, carbon-fibre-reinforced plastics — do not suffer from fatigue. This is an astonishing assertion, given that from the earliest days of the development of composites, their fatigue behaviour has been a subject of serious study, and what is usually implied is that, because most CFRP are extremely stiff in the fibre direction, the working strains in practical components at conventional design stress levels are usually far too low to initiate any of the local damage mechanisms that might otherwise have led to deterioration under cyclic loads.

The idea of using composites, especially CFRP, only at very low working strains raises two important issues. The first is the obvious one that by using expensive, high-performance materials at small fractions of their real strength, we are over-designing or, in more cost-conscious terms, we are using them uneconomically. The second is that since anisotropy is a characteristic that we accept and even design for in composites, a stress system that develops only a small working strain in the main fibre direction may easily cause strains normal to the fibres or at the fibre/resin interface that may be high enough to cause the kind of deterioration that we call fatigue damage. In designing with composites, therefore, we cannot ignore fatigue. And it follows directly that, in addition to needing to understand the mechanisms by which fatigue damage occurs in composites, we need access to procedures by which the development and accumulation of this damage, and therefore the likely life of the material (or component) in question, can be reliably predicted.

One can concentrate mainly on the fatigue behaviour of polymer-matrix composites. Since the majority of accessible research studies have concerned these materials, it is inevitable that even a general picture of composites fatigue will be substantially coloured by our knowledge of fibre-reinforced plastics (FRPs). Specific reference to metal- and ceramic-matrix composites will be made after a discussion of FRPs. Automotive components are subjected to the cyclic loading during the operation, which leads to fatigue crack and propagation of the crack due to the local fatigue damage. The fatigue failure prevents the components from functioning properly, and causes the critical problems in vehicle safety. Therefore, in order to secure the automotive components against fatigue failures, durability test of the assembly of the components has been performed in the automotive industries. Recently, at the early stage of the vehicle development, fatigue design and durability analysis are applied for the chassis systems such as power transmission, suspension, steering, and brake which are critically important for the vehicle safety.

A column in the steering system is a component which transmits steering forces between Pittman arm in the steering shaft and a steering arm in the knuckle. Steering column consists of link rod, and ball joints. In this paper, in order to ensure the reliability of the link assembly in the steering system, the fatigue analysis of the link was performed by incorporating the finite element stress analysis of the link assembly and the low-cycle fatigue test of the link material. Predicted fatigue life of the link was compared to the experimentally determined fatigue life to evaluate the validity and accuracy of the fatigue analysis. Composites are defined as the materials that contain fibers embedded in a resin matrix. The aim of combining fibers and resins that are different in character is to take advantage of the unique material features of either component to result in an engineered material with desired overall composite action for particular applications.

2. Experimental Analysis

In order to estimate the life of the column, fatigue tests were conducted using a hydraulic test system as shown in figure 1. The hydraulic test system consisted of an actuator of 100 kN capacity, reaction fixtures, a controller, load cell, servo – pump system. A strain measurement system was also used for measuring the local strains at the curved region of the steering rod. Cyclic loads of constant amplitudes with a sinusoidal waveform are applied to the link assembly.

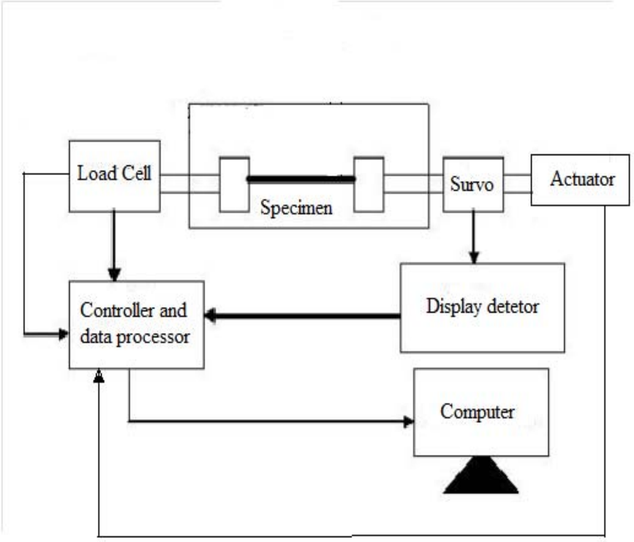

Fig. 1 Experimental Setup

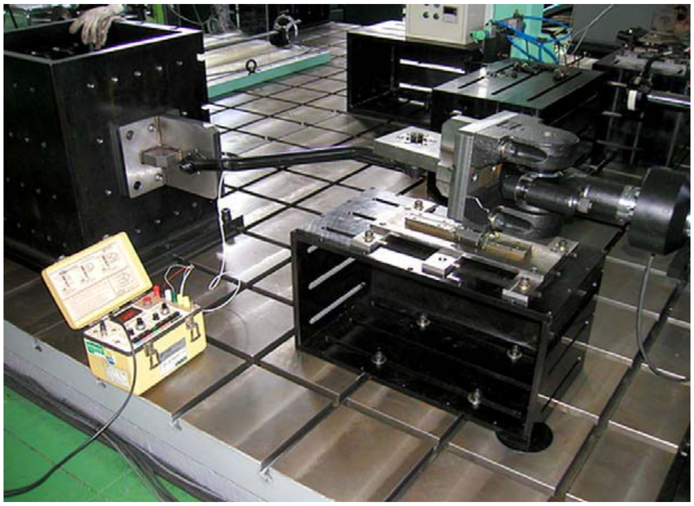

Fig. 2 Hydraulic Experimenal Setup

3. Application of the Finite Element Method in Fatigue Analysis

3.1 Types of fatigue analysis

- Strain Life (Available in ANSYS Fatigue Module)
- Stress Life (Available in ANSYS Fatigue Module)
- Fracture Mechanics

3.1.1 Strain Life

Strain can be directly measured and has been shown to be an excellent quantity for characterizing low-cycle fatigue. Strain Life is typically concerned with crack initiation. In terms of cycles, strain life is typically useful for low number of cycles and therefore addresses Low Cycle Fatigue (LCF), but it also works with high numbers of cycles as well. Low cycle fatigue usually refers to fewer than 10^5 (100,000) cycles. At present the strain life approach is widely used.

The Strain Life Relation equation is shown below:

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

Where,

$\frac{\Delta\varepsilon}{2}$ = Total strain amplitude

σ'_f = Fatigue strength coefficient

E = Modulus of elasticity

N_f = Number of cycles to failure

b = Fatigue strength exponent

ε'_f = Fatigue ductility coefficient

c = Fatigue ductility exponent

For Strain Life, the total strain (elastic + plastic) is the required input. But, running an FE analysis to determine the total response can be very expensive and wasteful,especially if the nominal response of the structure is elastic. So, accepted approach is to assume a nominally elastic response and then make use of Neuber's equation to relate local stress/strain to nominal stress/strain at a stress concentration location.

To relate strain to stress we use Neuber's Rule, which is shown below:

$$\varepsilon\,\sigma = K_t^{\,2} e\, S$$

Simultaneously solving Neuber's equation along with cyclic strain equation, we can calculate the local stress/strains (including plastic response) given only elastic input. Note that this calculation is nonlinear and is solved via iterative methods. ANSYS fatigue uses a value of 1 for Kt, assuming that the mesh is refined enough to capture any stress concentration effects.

3.1.2 Stress Life

Stress Life is based on S-N curves (Stress – Cycle curves).Stress Life is concerned with total life and does not distinguish between initiation and propagation. In terms of cycles, stress life typically deals with a relatively high number of cycles. High number of cycles is usually refers to more than 10^5 (100,000) cycles. Stress life traditionally deals with relatively high numbers of cycles and therefore addresses High Cycle Fatigue (HCF), greater than 10^5 cycles inclusive of infinite life.

3.1.3 Fracture Mechanics

Fracture Mechanics starts with an assumed flaw of known size and determines the crack's growth. Facture Mechanics is therefore sometimes referred to as "Crack Life". Facture Mechanics is widely used to determine inspection intervals. For a given inspection technique, the smallest detectable flaw size is known. From this detectable flaw size we can calculate the time required for the crack to grow to a critical size. We can then determine our inspection interval to be less than the crack growth time. Sometimes, strain life methods are used to determine crack initiation with fracture mechanics used to determine the crack life therefore,

Crack Initiation + Crack Life = Total Life

4. Results and Discussion

4.1 Materials

Joris Degrieck and Wim Van Paepegem, [1], in this paper, they have studied the major fatigue models and life time prediction methodologies for fiber reinforced polymer composites, subjected to fatigue loading. He has also studied the fatigue models have been also classified in three different categories such as fatigue life models in which actual degradation mechanisms has not considered but priory use the S-N curves or Goodman diagrams, Phenomenological models used for determination of residual stiffness and residual strengths and progressive damage models which consider some damage variables.

M.A. Badie, E. Mahdi, and A.M.S. Hamouda, [2], in this paper they have studied the effect of fiber orientation angles and stacking sequence on the torsional stiffness, natural frequency, buckling strength, fatigue life and failure modes of composite tubes. Finite element analysis has been used to predict the fatigue life of composite drive shaft using linear dynamic analysis for different stacking sequence. Experimental program on scaled woven fabric composite models was carried out to investigate the torsional stiffness. FEA results showed that the natural frequency increases with decreasing fiber orientation angles.

Christopher S. Grimmer and C.K.H. Dharan, [3], these two researchers studied that the addition of small volume fractions of multi-walled carbon nanotubes (CNTs) to the matrix of glass–fiber composites reduces cyclic delamination crack propagation rates significantly. In addition, both critical and sub-critical inter-laminar fracture toughness values are increased. These results corroborate recent experimental evidence that the incorporation of CNTs improve fatigue life by a factor of two to three in in-plane cyclic loading. They also studied that in both the critical and sub-critical cases, the degree of delamination suppression is most pronounced at lower levels of applied cyclic strain energy release rate. High-resolution scanning electron microscopy of the fracture surfaces suggests that the presence of the CNTs at the delamination crack front slows the propagation of the crack due to crack bridging, nanotube fracture, and nanotube pull-out.

A.Mohamed Ansar, Dalbir Singh and Balaji.D, [4], in this paper they have studied the composites focusing on some structure materials can match the flexibility and effectiveness of glass fiber Reinforced plastic, commonly called GFRP for short or simply fiberglass. Even it is very high strength, light weight, strong, and completely waterproof, it can be molded into free form shapes such as aerospace structures, and then also it has its endurance limits. Endurance limit means loss of strength and stiffness. This article describes about the fatigue life material properties of GFRP composites are studied based on an extensive experimental study.

S. Daggumati and I. De Baere, et al. [5], in this paper they have studied the experimental fatigue damage analysis of a carbon-PPS 5-harness satin weave composite under tension–tension fatigue. Evolution of the longitudinal strain as well as the longitudinal stiffness of the composite specimen was monitored throughout the cyclic load process. During the fatigue test, instrumentation of the composite structural response is categorized into two parts: (i) the first priority was to monitor the macro-scale structural response such as the increase in the longitudinal strain and hence decrease in the composite longitudinal stiffness; (ii) the second priority was to capture the micro-scale damage events which are occurring in correlation with the observed fluctuations in the macro-scale structural response.

Hai C. Tang and Tinh Nguyen, et al. [7], They have developed the fatigue damage model for predicting the life of FRP composites. This model consist of applied maximum stress, stress amplitude, loading frequency, residual tensile modulus and material constant as parameters. The model data is verified with experimental fatigue data on a glass fiber/vinyl ester composite. While the specimens are exposed to air, fresh water, at 30^0, they are subjected to tension-tension stress at four levels of applied maximum tensile stress in each of two frequencies. The results have been concluded that for material used in this study, the loss in residual tensile strength and modulus in saltwater is approximately the same as that in freshwater and that the fatigue life in these aqueous environments is shorter than that in air. Numerical analysis is carried out to determine the material constants.

Brian Burks, James Middleton and Maciej Kumosa, [8], they have studied initiation of fatigue damage for a hybrid polymer matrix composite material was studied via 3-Dimensional viscoelastic representative volume element modeling in order to gain further understanding. It was studied that carbon fiber reinforced composites perform better in fatigue loading, in comparison to glass fiber reinforced composites, because of the fact that the state of stress within the matrix material was considerably lower for carbon fiber reinforced composites eliminating fatigue damage initiation. The effect of polymer aging was also evaluated in this study through thermal aging of neat resin specimens. Short-term viscoelastic material properties of unaged and aged neat resin specimens were measured using Dynamic Mechanical Analysis. With increasing aging time a corresponding increase in storage modulus was found. Increases in the storage modulus of the epoxy matrix subsequently resulted in a higher state of predicted stress within the matrix material from representative volume element analyses. Various parameters common to unidirectional composites were numerically investigated and found to have varying levels of impact on the prediction of the initiation of fatigue damage.

4.2 Stress - Strain Amplitudes

S. Daggumati and I. De Baere, et al. [5], in this paper they have studied the experimental fatigue damage analysis of a carbon-PPS 5-harness satin weave composite under tension–tension fatigue. Evolution of the longitudinal strain as well as the longitudinal stiffness of the composite specimen was monitored throughout the cyclic load process. During the fatigue test, instrumentation of the composite structural response is categorized into two parts: (i) the first priority was to monitor the macro-scale structural response.

F. Walther and D. Eifler, [9], in this paper, they investigated the stress-controlled fatigue tests with SAE 1050 and SAE 1065 specimens were performed under single step and random loading to study fatigue mechanisms with particular attention to micro structural details. The applied plastic strain amplitude, temperature and electrical resistance measurements depend on deformation-induced changes of the microstructure and represent the actual fatigue state of the investigated steels. A new test procedure combines any kind of load spectra with periodically inserted single step sequences to measure the plastic strain amplitude, the temperature and the electrical resistance. The average values of the measuring sequences are plotted as function of the number of cycles in cyclic deformation curves and represent the summation of micro structural changes caused by random loading. Electrical resistance measurements allow to detect the proceeding fatigue damage even in the load free state. On the basis of comprehensive experimental fatigue data the physically based lifetime calculation method ‘‘PHYBAL’’

M. Firat and U. Kocabicak, [10], in this paper, the result of the commercial pressure new methods of durability evaluation have to be explored, automotive suppliers are now being asked to develop new components and subsystems in shorter times and using fewer physical prototypes. It is necessary to verify the existing methods for the durability assessment have been increasing and this turns out to be the only way to propose new computational models to validate the final product within these reduced time scales and resources. The paper reviews some of the computational aspects of fatigue damage analysis and life prediction, and a practical fatigue evaluation tool is presented to meet this challenge.

T. Ingrassia, G. Lo Buglio and E. Lombardo, et al. **[**11], in this paper, they have investigated a novel self-balanced internal combustion engine is presented. The new engine has a modular structure composed of two cylinders arranged in opposite way. Its useful to have particular shape of the shaft so that the pistons can move with the same timing and so the new engine comes back to be perfectly auto-balanced. Moreover, the fatigue life prediction of the shaft has been studied through numerical methods. In particular, two different approaches have been compared to estimate the maximum number of working cycles: the first is based on a “static” resistance criterion, the second considers the multiaxial nature of the stress and is based on the maximum shear stress (critical) plane criterion. The stress distribution on the shaft during the usual working conditions has been evaluated by a FEM package. Results highlight that the critical plane approach is more conservative than the static one. [5]

4.3 Loading Frequency

M.A. Badie, E. Mahdi, and A.M.S. Hamouda, [2], In this paper they have studied the effect of fiber orientation angles and stacking sequence on the torsional stiffness, natural frequency, buckling strength, fatigue life and failure modes of composite tubes. Finite element analysis has been used to predict the fatigue life of composite drive shaft using linear dynamic analysis for different stacking sequence. Experimental program on scaled woven fabric composite models was carried out to investigate the torsional stiffness. FEA results showed that the natural frequency increases with decreasing fiber orientation angles.

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4.4 Stress Concentration Factor

Hui Jiao, Fidelis Mashiri and Xiao-Ling Zhao, [12], in this paper, they have investigated the fatigue behavior of very high strength steel tubes to steel plate T-joints joints under cyclic in-plane bending. VHS tubes, with a yield stress of 1350 MPa and an ultimate tensile strength of 1500 MPa, were welded to G350 steel plates using the GTAW welding method. Three different failure modes were observed. Stress concentration factors ranging from 1.2 to 2.2 were obtained through linear extrapolation at the weld toe. The fatigue life of VHS to plate T-joints was determined using the hot spot stress approach with a stress concentration factor as a testing parameter.

5. Conclusion

The conclusion drawn from the present studies that the various parameters used by some researchers to calculate number of cycles for fatigue failure such as material constant, stress – strain amplitude, loading frequencies, stiffness, etc. But these parameters are not sufficient for whole study of the component. Some parameters has to be chosen for developed study for fatigue analysis. I have studied the properties for fiber reinforced composites and glass fibers composites and also studied their analysis.

The material replacement has an maximum influence on fatigue life of steering column. The composite material will give upto 2 to 3 times maximum torsional strength, the better stiffness values. Loading frequencies can cause the component to go under cyclic loading. Due to loading there is always stress concentration in the critical parts which causes crack formation in the component. Study of stress concentration factor helps to optimize the life of component.

In this dissertation, study of different research paper has been done and also it helps to identify new parameters which are required for the fatigue testing and analysis. By considering the parameters, it is possible to do further dissertation work. That is it is possible to increase the strength and lighten the weight of steering column. These parameters useful to overcome the past problems came while doing those studies. This dissertation work will be useful in industry for increasing the life of the composite component with maximum efficiency and higher properties than conventional materials.

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