Fatigue and Buckling Strength Analysis of the Wing Hinge in the Creo Simulation Environment

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Received: January 10, 2013 / Accepted: February 7, 2013 / Published: April 25, 2013.

Abstract: This paper provides background information on fatigue and describes the methodology used in Creo Simulation (Pro/Mechanica) fatigue analysis. It covers history and physics of fatigue, the E-N approach—Strain Cycles Includes the effect of mean residual stresses, hysteresis loop capture and rainflow cycle counting. Factors that affect fatigue life include component size, loading type, surface finish, surface treatment and effect of surface treatments on endurance limit. This paper describes practical problem solution and fatigue strength analysis of the wing-hinge to fuselage connection in Creo Simulation (Pro/Mechanica) environment. It also includes a procedure for calculating the buckling load factor and failure index.

Key words: Fatigue, Creo Simulation, Pro/Mechanica, S-N diagram, E-N diagram, rainflow cycle counting, Wöhler line, CAE (computer aided engineering), CAD (computer aided design), log life, confidence of life, failure index, BLF (buckling load factor).

1. Introduction

The majority of component designs involve parts subjected to fluctuating or cyclic loads. Such loading induces fluctuating or cyclic stresses that often result in failure by fatigue. About 95% of all structural failures occur through fatigue mechanism. Between 1852 and 1870, August Wöhler, a German railway engineer, set up and conducted the first systematic fatigue investigation. His data were plotted, in terms of nominal stress (S) vs. number of cycles to failure (N), what has become known as the S-N diagram (Wöhler line) [1].

2. History and Physics of Fatigue

The physical development of a crack is generally divided into two separate stages, bearing relation to the phase of crack initiation phase and crack growth. Fatigue cracks are initiated through the release of shear strain energy. Following the 2nd stage, the crack propagates perpendicularly to the direction of the applied load. As the physical mechanism for fatigue is

divided into two stages, the methods of analysis are also divided into two stages. The 1st stage is a typically analysis based on the local strain (E-N) approach, while the 2nd stage is an analysis based on the fracture mechanics approach. A complete fatigue prediction could therefore combine both methods: Total Life = Life to initiation + Life taken to propagate crack to failure.

Many aerospace applications use flexible components made of very ductile materials. In such cases, cracks propagate relatively slowly, so the fracture mechanics approaches are considered more appropriately.

The S-N analysis is unsuitable for performing CAE analysis on components containing local areas of plasticity because it uses elastic stress as the input and fatigue initiation is driven by local plastic strain. For this reason, methods based on local strain (E-N) are more universally suitably. To this product, the E-N approach has been applied [1].

3. The E-N Approach

The E-N approach uses fatigue tests, subjected to various types of cyclic loading, such as small-scale bending, torsion, tension and compression to measure

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fatigue life. The results are plotted in terms of strain (ϵ) vs. cycles to failure (N) on an E-N diagram.

Owing to variable amplitudes of loading, it is necessary to extract the fatigue damaging cycles from the signal before starting the evaluation of the damage inflicted by each cycle. The total damage is the sum of the damage caused by each individual cycle. Each fatigue cycle is extracted by a process known as the hysteresis loop capture.

Creo Simulation uses a generic set of fatigue properties to model low alloy steels, unalloyed steels, aluminium alloys and titanium alloys. A very efficient algorithm has been developed to perform cycle extraction, known as rainflow cycle counting. It is the algorithm that Creo Simulation uses (Fig. 1).

When a stress-strain hysteresis loop is closed, then the strain range and mean stress are reverted and the damage calculated using the E-N curve modified for mean stress correction. The analysis was carried out over the whole strain time signal until all the cycles have been extracted and the total damage evaluated.

Creo Simulation usually uses a linear elastic solution to determine the pseudo-elastic strains in a component. The solution ignores the plasticity. Before proceeding with the fatigue analysis, these strains are automatically converted into non-linear elastic-plastic strains using Neuber's relationship.

There are some factors that affect fatigue life (component size, loading type, surface finish). For example, if an axial tension load produces a strain ϵ , the strain produced under a bending load would be 1.25ϵ . If machining reduces the endurance limit by 30%, then cold rolling will recover the loss by increasing the limit to 70% [2].

4. Problem Solution by Creo Simulation

We are designing a wing-to-fuselage connection. One of the components, where analysis is required, is the wing hinge (Fig. 2).

Wing hinges have never been known to fail through fatigue in the past but we are now required to prove this before the component progresses to the next stage in

Fig. 1 Rainflow cycle counting algorithm.

Fig. 2 CAD models of the wing hinges.

the design. To our estimates, the wing hinge has a maximum tensile force of 15000 N applied to the connecting hinge eye (Fig. 2). The material chosen is steel (For details see Fig. 3). The new wing hinge has a target life of approximately 10 million cycles under a peak-to-peak loading (Fig. 3). The results of both the static and fatigue analyses are presented in Figs. 4-6.

Material Definition

Name: STEEL

Description:

Density: 7.82708e-09 tonne/mm³

Appearance: User Defined

Structural: Thermal: Miscellaneous:

Symmetry: Isotropic

Stress-Strain Response: Linear

Poisson's Ratio: 0.3

Young's Modulus: 210000 MPa

Coeff. of Thermal Expansion: 1.17e-05 /C

Mechanisms Damping: sec/mm

Material Limits:

Tensile Yield Stress: 300 MPa

Tensile Ultimate Stress: 1000 MPa

Compressive Ultimate Stress: MPa

* Required Fields

Failure Criterion: Distortion Energy (von Mises)

Fatigue: Unified Material Law (UML)

Material Type: Low Alloy Steels

Surface Finish: Good Machined

Failure Strength Reduction Factor: 1

OK Cancel

Fatigue Analysis Definition

Name: Fatigue

Description:

Load History: Previous Analysis

Life: Desired Endurance: 1e+07 cycles

Loading: Type: Constant Amplitude

Amplitude Type: Peak-Peak

Min Load Factor: -1

Max Load Factor: 1

Output: Plotting Grid: 4 ☒ Calculate factor of safety

OK Cancel

Fig. 3 Material property form and fatigue analysis form.

Fig. 4 Stress von Mises and fatigue log-life plots.

Fig. 5 Fatigue confidence of life and fatigue factor of safety plots.

Fig. 6 Failure index plot.

5. Conclusions

Look at the results from the static stress and log life plots (Fig. 4). Notice where the fatigue cracks are likely to form. The minimum log life is 6.636 that means $10^{6.636}$ or 4325 138 cycles at a point where the Stress von Mises has its maximum of 225 MPa. Have a look at the other plots (Fig. 5). Notice how the confidence of life is all green. The minimum factor of safety suggests a permissible overload before fatigue life is jeopardized.

Creo Simulation does not analyze plastic behavior. That is something the user must check for. When the model stress exceeds the material yield stress, it has permanently deformed and will not return to its original shape. Creo Simulation treats the stress-strain curve as if it is linear even beyond the yield stress point. The way we check to see if the material is plastically deformed is to see if the calculated stress levels exceed the material Yield Stress. This means that we must be aware of the yield stress, or yield strength, of the material we are using. Although strictly speaking, material does not fail in the plastic region. Creo Simulation considers the plastic region to be failure. Creo Simulation's Failure Strength is the level of stress at which the material starts to plastically deform. We select a failure determination method, then enter the cutoff stress limit for that method (Fig. 3) [2].

Creo Simulation results allow you to plot a failure index measure with a color fringe plot (Fig. 6). The calculated stresses are compared to the cutoff stresses and an index is plotted. The index is interpreted as follows: Less than 1—Material has not yielded. In this Case, failure index is 0.7 max. Equal to or greater than 1—Material has yielded. The color legend can be adjusted so that failure indexes greater than 1 are colored red. This way we can look at the result window for the color red. Red would indicate that under the applied load the material has failed, or that the calculated stress has exceeded our limit [3].

The results of a previously run static analysis are the starting point for a buckling analysis. Creo Simulation buckling analysis is a linear eigenvalue bifurcation instability analysis. It will check to see if the model will

buckle under a given compressive loading condition. The BLF (Buckling Load Factor) is the magnification factor by which the loads applied in a previous specified static analysis would have to be multiplied to produce the critical buckling load: BLF less than 1—Model has buckled. BLF greater than 1—Model has not buckled. In this case, BLF = 103 for maximum compressive force of wing hinge 15000 N [4].

Creo Simulation buckling analysis will typically overestimate the buckling load in comparison to real world tests. This means the Creo Simulation buckling load is somewhat high, and that the part may buckle below the buckling load that Creo Simulation predicts. We should divide the Creo Simulation BLF by a factor of 2-3 in order to provide a conservative solution. For stress results, we should use the static analysis results. For stress results at the area of buckling, multiply the stresses from the static analysis (Fig. 4) with the buckling load factor. The buckling load factor can be used as a limit in Creo Simulation optimization studies [4].

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