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METHODOLOGY FOR REPEATED LOAD ANALYSIS OF COMPOSITE STRUCTURES WITH EMBEDDED MAGNETIC MICROWIRES

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Preliminary Note – Prethodno priopćenje

The article processes issue of strength of cyclically loaded composite structures with the possibility of contactless stress measuring inside a material. For this purpose a contactless tensile stress sensor using improved induction principle based on the magnetic microwires embedded in the composite structure has been developed. The methodology based on the E-N approach was applied for the analysis of the repeated load of the wing hinge connection, including finite element method (FEM) fatigue strength analysis. The results proved that composites in comparison with the metal structures offer significant weight reduction of the small aircraft construction, whereas the required strength, stability and lifetime of the components are remained.

Key words: fatigue strength analysis, magnetic microwires, composite structures, FEM

INTRODUCTION

The increased use of advanced composite materials on primary aircraft structures has initiated the discussion of how such structures perform under repeated loading, forasmuch as there are many clear differences between composite and metal materials. Some of the methods solve specific problems, such as for example effects of fiber-matrix interface to track damage creation at smaller scales, tension-dominated fatigue loading, amplitude fatigue loading or multiaxial loading [1, 2]. Also many analytical models have been developed, such for example statistical model to predict probability of failure for cross-ply laminates [3], cohesive model for modeling of delaminations during high cycle fatigue [4] or finite element model with built-in stiffness and strength degradation [5]. Models usually require basic S-N curves known also as the Wöhler lines, but the problem is with the out-of plane dominating loading. For these cases only heuristic or semi-empirical approaches have been developed [6, 7].

THE E-N APPROACH

Till now there is no comprehensive analytical model for composites that can be used to predict fatigue behavior with all the parameters and variables, but the modeling itself is always based on the understanding of the damage creation. Our research is focused on the E-N approach using fatigue tests, subjected to various types of cyclic loading, such as small-scale bending, torsion, tension and compression to measure fatigue life of composite structures with embedded magnetic microwires that enable non-destructive contactless tensile stress sensing based on the improved induction method.

K. Semrád, K. Draganová, Faculty of Aeronautics, Technical University of Kosice, Slovakia

DEFINITION OF COMPOSITE MATERIALS

The presented article deals with the design of a composite wing to fuselage connection (Figure 1) consisting of the Std Carbon Fibre Fabric / Epoxy Resin with embedded microwires. The thickness of each layer was 0,6 mm and the layer orientation angles were 0°, 45°, 90°.

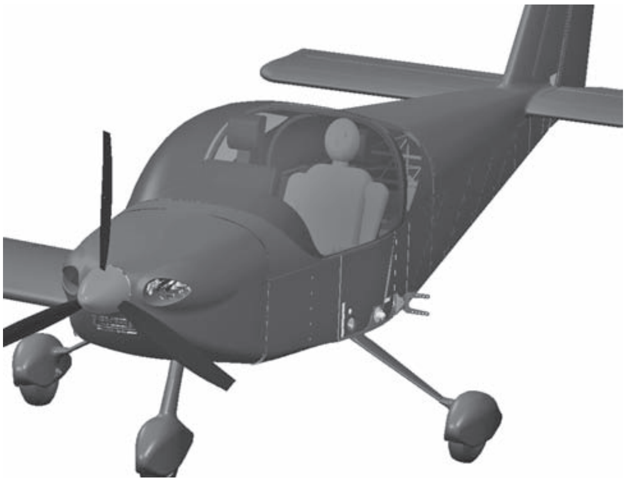

Figure 1 Wing hinge in aircraft structure

MICROWIRE-BASED TENSILE STRESS SENSORS

Forasmuch as because every model is in principle simplified, it would not have to capture the material behavior correctly and would not be sufficiently accurate for every specific situation. Therefore periodic structural monitoring is necessary. Our research is focused on the contactless embedded microwire-based sensor for the aircraft construction monitoring using the amorphous Fe-based glass-coated magnetic microwires consisting of a metallic core with the diameter of 0,6 – 30 μm and of glass coat with the thickness of 2 – 20 μm. Thanks to their dimensions, electrical, magnetic and mechanical properties microwires can be embedded into the composite structures and serve as a sensing element of a tensile stress sensor [8, 9].

To determine the microwire properties of it is appropriate to use such a method that allows a direct component separation of the switching field. It is convenient to use a method which directly determines the critical switching field, which is actually equivalent to the coercivity. Result of this problem solution is a special induction method that has been developed at our Department [10], which uses an exciting coil supplied by the precision triangular-shaped current and the sensing coil for the domain wall motion detection represented as induced voltage peaks. While the exciting field has the triangular shape, the switching field is proportional to the time at which the peak appears. The time shifts between the exciting magnetic field and induced voltage peaks allow to determinate the switching field by the time interval measuring using the Complex Programmable Logical Device (CPLD).

During the experiment the measuring microwire with the length of 2 cm and with the chemical composition $Fe_{38,5}Ni_{39}Si_{7,5}B_{15}$ was embedded between two glass woven layers bonded by the LH 160 aviation epoxide resin certified by the Germanische L´loyd. Measurements consisted of the static mechanical loading of this sample in the range of 0 – 1 000 N. Further the response to the dynamic change of the mechanic tensile stress by the constant external magnetic field was measured.

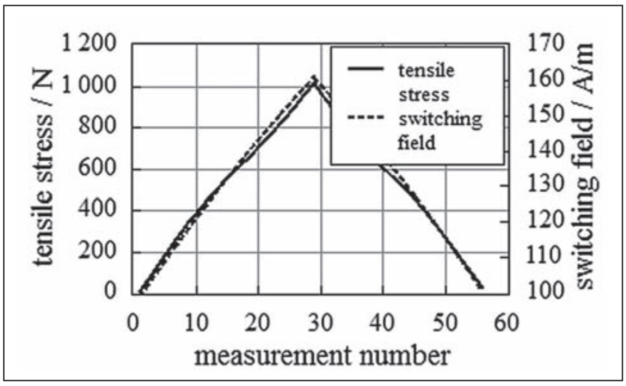

Figure 2 Microwire's response to applied tensile stress

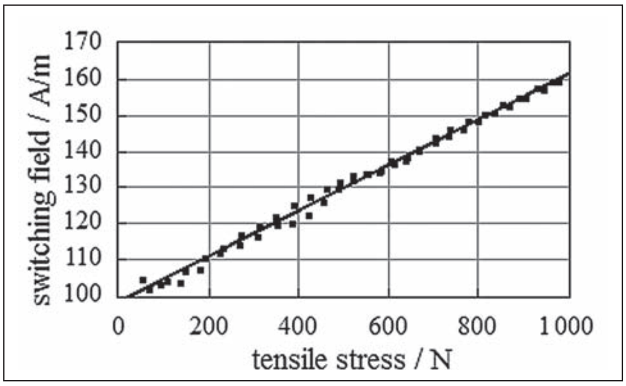

Figure 3 Microwire's static conversion characteristics

The performed tests showed and also confirmed the assumed good mutual separability of the tensile stress from the external magnetic field in the low-frequency area. As it can be seen from the Figure 2 and Figure 3, the microwire response is in a very good relation to the applied tensile stress. The presented results are confirming good adhesion of the microwire in the composite material sample and clearly detectable response of the microwire to the tensile stress induced inside the tested sample.

Measurement of the tensile stress can be performed either on the material surface as in case of conventional strain gauge measuring methods or inside of the material because microwire can be thanks to their small dimensions easily integrated directly under the surface of the tested construction in any place without structural violations and without changes in material characteristics. In case of using our improved induction methodology the measurement is completely contactless.

SIMULATIONS AND RESULTS

The problem solution was performed using Creo Simulation software. For the calculation were chosen predefined material properties like "transversely isotropic" for the maximum stress criterion used. Composite materials are characterized by different material properties in each direction. That's the reason why it is so important to choose the right material orientation for optimal composite properties applications. The strength calculations in module Creo Simulate are based on the geometric element method (GEM). The principle of this method, similar to the finite element method (FEM), is based on dividing the analyzed volume into elements. For the required accuracy there is used the P–adaptive method, which concludes the calculations with those the user can evaluate values like stress, deformation, etc.

Wing hinges have never been known to fail trough fatigue in the past but we are now required to prove this before the component progresses to the next stage in the design. To our estimates, the wing hinge has a maximum compressive force of 1 000 N applied to the connecting hinge eye. The material chosen is steel for the original component and composite for the new component. The wing hinge has a target life of approximately 10 million cycles under a peak to peak loading. The results of all analyses are presented in the Figure 4 and 5.

Look at the results of steel wing hinge from the static stress, displacement and log life plots (Figure 4). Notice where the fatigue cracks are likely to form. The minimum log life is 6,70498 that means $10^{6,70498}$ or 5 069 673 cycles at a point where the Stress von Mises achieves its maximum of 320 MPa. 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 has to check for. When the model stress exceeds the material yield stress, permanent deformations occur and material will not return to its original shape. Creo Simulation considers the stress-strain curve as linear even beyond the yield stress point. The way how to check if the material is plastically deformed is to verify whether the calculated stress levels exceed the material Yield Stress. That is the reason why the information about the yield stress or yield strength of the used material are required. 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 deform plastically. After failure determination method selection (Distortion Energy - von Mises) and entering the cutoff stress limit for the method (Tensile Yield Stress = 400 MPa) it is possible to plot a Failure Index measure with a fringe plot based on the simulation results. The calculated stresses are compared to the cutoff stresses and the index is plotted. The index can be interpreted as follows: Less than 1 - material has not yielded. In this case the Failure Index is 0,8 max. Equal to or greater than 1 - material has yielded, which means that under the applied load the material has failed, or that the calculated stress has exceeded the pre-defined limit.

The results of a previously run static analysis are the starting point for a buckling analysis – a linear eigenvalue bifurcation instability analysis that checks 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 previously specified static analysis would have to be multiplied to produce the critical buckling load (BLF < 1 means that model has buckled, BLF ≥ 1 model has not buckled). In this case BLF = 54 for the maximum compressive force of steel wing hinge 1 000 N.

The Creo Simulation buckling analysis will typically overestimate the buckling load in comparison to the real world tests. This means the 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 in order to provide a conservative solution. For the stress results, we should use the static analysis results. For stress results in the area of buckling, multiply the stresses from the static analysis with the buckling load factor. The buckling load factor can be used as a limit in the Creo Simulation optimization studies.

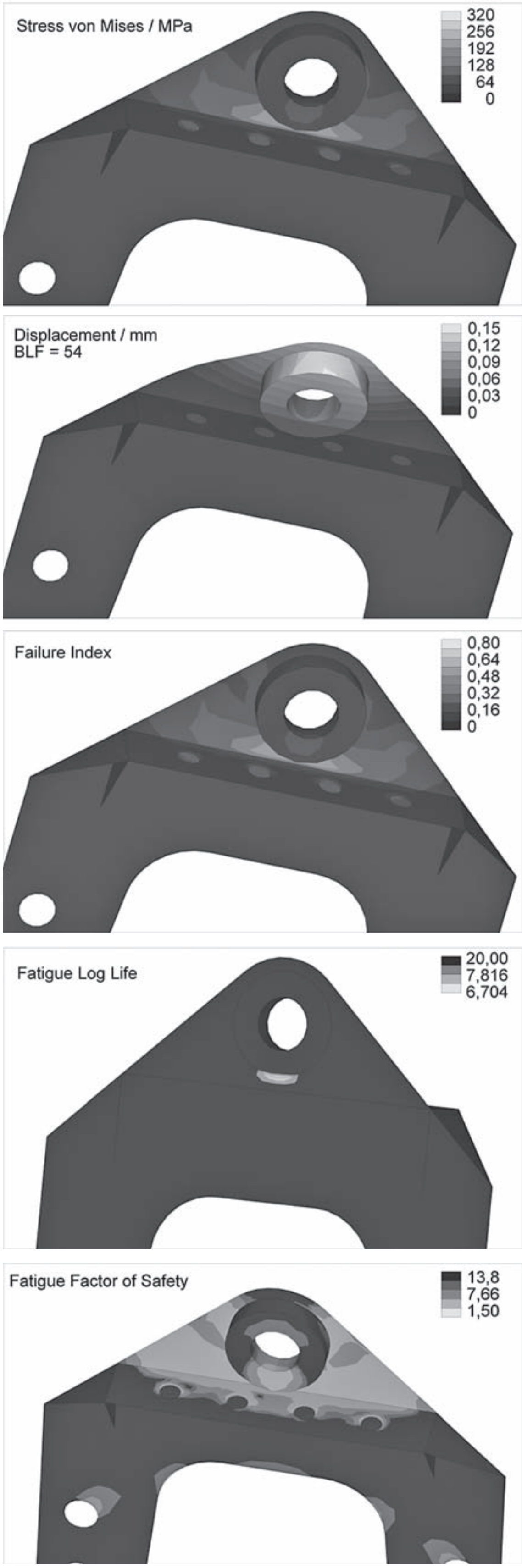

Figure 4 Steel wing hinge analysis

CONCLUSION

According to the results of composite wing hinge analysis that involves the static stress, displacement and buckling analysis shown in Figure 5 it can be seen that BLF = 13, Max. Stress von Mises = 134 MPa < Ultimate Tensile Strength (600 MPa) and Ultimate Compressive Strength (570 MPa). Stress Max. Shear = 73 MPa < Ultimate In-plane Shear Strength (90 MPa). The

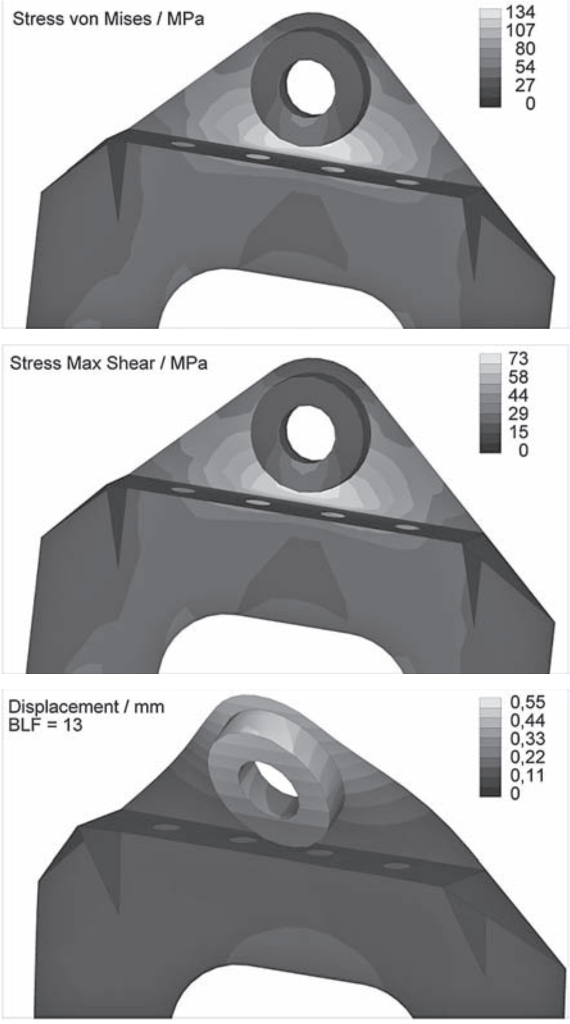

Figure 5 Composite wing hinge analysis

total mass of the new composite wing hinge is 0,04 kg < total mass of the original steel wing hinge (0,13 kg).

For the verification and monitoring of the E-N approach results we designed contactless non-destructive tensile stress sensors based on the magnetic microwires embedded in the fully composite wing hinge structure to monitor composite material characteristics in critical points.

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Note: The responsible translator for English language is Katarína Draganová from Technical University of Kosice, Slovak Republic